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FLIGHT OF AIRCRAFT WITH PARTIAL AND UNBALANCED THRUST

by M. L. Gallay

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ANNOTATION

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Flight of Aircraft with Partial and Unbalanced Thrust. Gallay, M.L., "Mashinostroyeniye," Moscow, 1970, 192 pp.

The book investigates the motion of multiengined aircraft flying with partial and unbalanced thrust as a result of failure of engines.

Consideration is given to the probability characteristics of such flight, the manner in which external factors and the aerodynamic parameters of the aircraft influence it, steady route flight, landing approach, and landing and takeoff with partial powerplant failure.

A special chapter is devoted to the standards for airworthiness of aircraft, which codify their characteristics for cases of engine failure, and methods of determining conformity to them in flight tests.

In setting forth the material, a special attempt has been made to bring out the physics of the phenomena governing the divergent motion of the aircraft.

The book is intended for design-office, test-station, and user-organization engineers, as well as for flight crews. At the same time, it should be helpful to instructors and students at the aeronautical higher educational institutions. With 3 tables, 85 illustrations, and a bibliography with 23 source citations.

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*Numbers in the margin indicate pagination in the foreign text.

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FOREWORD /3

The extensive use made of multiengined aircraft in modern aviation has resulted in a substantial improvement of flight safety, but at the same time the probability of failure of one or more engines among those forming the powerplant of the multiengined aircraft has increased accordingly.

Thus the problem of flight with partial and unbalanced thrust has now become a highly urgent one.

The present volume deals with a range of problems related to the dynamics of the divergent motion of the aircraft immediately after failure of an engine (in particular, a lateral engine, i.e., one located outside the plane of symmetry of the vehicle), to the parameters of the steady flight regime that follows, to execution of the necessary maneuvers – turns, landing approach, landing – and to the influence of the airplane's design parameters and pilot handling on the course taken by the above processes.

The author has made a special effort to present the physical essentials of the phenomena that attend flight with partial and unbalanced thrust. Not all of the cases of such flight that are examined in this book are equally probable in practice. For certain types of aircraft, e.g., passenger aircraft, many of them would be correctly regarded as inadmissible. Nevertheless, it is best not to exclude them from consideration, firstly because the occurrence of such cases is possible on aircraft of other types and, secondly, because their analysis is helpful in understanding the nature of the unfolding phenomena. Moreover, many situations that are inadmissible in normal operations may arise in flight tests.

The practical recommendations given in the book are of two kinds: some of them are addressed to design-organization workers and concern parameters that ensure acceptable properties of the aircraft in flight with partial and unbalanced thrust, while others are meant for the flight crew and contain guidelines for optimum /4 piloting in this rather complicated flight situation.

Considering the category of readers to whom the book is recommended, the author has considered it possible to employ the generally known propositions of the standard aircraft aerodynamics course without any supplementary explanations. Most of the symbols used in the book are standard in the literature on aerodynamics and flight dynamics. In the occasional cases in which a new or unfamiliar designation is introduced, it is explained immediately in the text.

Over a number of years, many important aspects of the problem of flying an airplane with partial and unbalanced thrust have been illuminated by V.F. Bolotnikov, V.S. Vedrov, A.A. Kalachikov, N.V. Lebedev, V.S. Lunyakov, M.I. Mazurskiy, V.N. Matveyev, I.V. Ostoslavskiy, A.I. Okhonskiy, V.S. Pyshnov, A.L. Raykh, D.A. Sorkin, V.G. Tabachnikov, M.A. Tayts, A.V. Chestnov, L.K. Chumachenko, and other scientists, engineers, and pilots. The author has made use of their results in this volume.

Moreover, in preparing the book for publication, the author had the opportunity to supplement his own experience in test-flying multiengined aircraft of various types with partial and unbalanced thrust in extremely valuable consultations with Ya.I. Vernikov, Honored Test Pilot of the USSR, and Candidate of Technical Sciences N.G. Shchitayev, and also profited by the remarks of the book's reviewers, Doctor of Technical Sciences and Professor A.Ye. Donov and Candidate of Technical Sciences M.V. Rozenblat. I extend my cordial thanks to all of these persons.

The publisher and author will be pleased to receive reader comments on the content, exposition, and design of the book, which should be addressed to Moscow, B-66, 1-y Basmannyy per., 3, izd-vo "Mashinostroyeniye."

INTRODUCTION /5

During the early development of aviation, the powerplants of airplanes contained a single engine. Failure of this single engine in flight invariably resulted in either a crash or a forced landing.

Single-engined powerplants did not enjoy their monopoly for long. Only a few years passed before aircraft with two, three, and more engines began to appear in many countries. For example, the Russian four-engined "Il'ya Muromets" airplane, the German bimotor "Gotha" and others were used as early as in the First World War.

The development of multiengined aircraft proceeded without letup in the years that followed. The main reason for this appeared to be that the aviation engines of the time could not deliver the power needed as the weight and dimensions of the airplanes continued to increase. As a result, a trend toward a further increase in the number of engines made its appearance in the early 1930's. It was then that the eight-engined land-based ANT-20 "Maksim Gor'kiy" and the twelve-engined Dornier DO-X flying boat were built.

With the installation of two or more engines on an airplane, it became possible in principle to continue flight with partial thrust, i.e., flight after failure of one or more engines.

Even today, however, a failure of engines on one side is correctly regarded in aviation practice as one of the most complicated particular cases. Worldwide aviation experience indicates that it has resulted in disaster on more than one occasion. However, the same experience gives grounds for the statement that failure of a lateral engine does not mean that grave consequences are fatally inevitable. Two basic conditions must be met to ensure a favorable outcome in the event of one-sided engine failure: firstly, /6
layout and design of the airplane with use of the means known to present-day aviation engineering for ensuring acceptable controllability characteristics in flight with unbalanced thrust and, secondly, rational and deliberate actions on the part of the crew.

The title of the book includes two adjectives that characterize the performance of the powerplant after failure of one or more of the engines composing it: "partial" and "unbalanced." On aircraft of certain widely used configurations, e.g., two-engined aircraft, they are inevitably synonymous: partial thrust is invariably unbalanced at the same time.

In the general case, however, separate manifestations of these criteria are conceivable. Thus, when the central engine of a three-engined aircraft fails, powerplant thrust becomes partial, but it remains balanced. With certain types of aircraft (for example, the Soviet Be-30 passenger airplane), provision is made for installation of a synchronizing shaft that couples the propellers kinematically in such a way that when one engine fails, the power of the remaining engine is distributed symmetrically to both propellers. Conversely, if the engines of an airplane have an augmented-thrust reserve such that after failure of one of them the crew can still increase the thrust of the remaining engines to restore the original total thrust, flight will continue with unbalanced but full thrust.

The cases cited above are comparatively rare exceptions. Usually, failure of one or more engines of a multiengined airplane is equivalent to transition to flight with a thrust that is simultaneously both partial and unbalanced. It is this combined case — the most general one — that will be examined further in this book.

In recent years, the multiengined scheme has come into widespread use in both military and civil aviation. The impossibility of obtaining the required thrust from a single engine has not been the only reason for this. Modern aviation already has engines that develop thrusts of 15,000 to 20,000 kg and more. A second and no less important factor has been one of flight safety, which, as will be shown below, depends strongly on the composition of the powerplant.

Needless to say, other considerations, such as the total cost of the engines, convenience in operation, required ground servicing time, etc., also influence the decision as to the number of engines to be included in the powerplant of a given type of airplane. However, these considerations are less weighty than the aforementioned two basic ones.

At the present time (again clearly because of the increased /7 thrust delivered by modern engines and their increased reliability), powerplants consisting of six, eight, or more engines are almost never used.* An example that is characteristic in this respect is the development of a family of heavy transonic aircraft by the American firm Boeing: while this firm's B-52 strategic bomber was designed with eight engines, later Boeing aircraft of similar configuration — the C-135 aerial-refueling tanker and the 707 jetliner each carried only four more powerful engines, and the number has even been reduced to three in the Boeing 727.

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*Vertical-takeoff aircraft, which may have larger numbers of engines, represent an exception in this respect. However, such vehicles are not considered in this book.

The contemporary view, which is reflected in the requirements of the International Civil Aviation Organization (ICAO), is that passenger aircraft to be used for flights across oceans, the Arctic, and broad uninhabited or sparsely populated desert regions must have no fewer than four engines.

The once-vanished three-engined configuration has again come into extensive use in recent years. It is embodied in the Soviet Tu-154 and Yak-40, the American Boeing 727, and the British BAC-111.

Thus, the three- and four-engined powerplants may be recognized today as dominant in the design of heavy aircraft.

As a rule, aircraft of lighter types, designed for medium-haul and local service, have two engines.

With this makeup of the aircraft pool, it is natural that the problem of flight with partial and unbalanced thrust has acquired particular urgency.

In considering partial powerplant failure from the standpoint of flight safety, it must, of course, be remembered that engine failure is only one of many possible dangerous phenomena that may arise in flight. It is also necessary to bear in mind the possibility of encountering powerful wind gusts, icing, fire, collisions with other aircraft or ground obstacles, and many others.

Statistics indicate that the failure of engines and engine systems is still one of the most frequently occurring forms of mechanical failure. It is no accident that almost every Flight Manual lists engine failure first in its tabulation of the so-called "special cases."

According to the ICAO, the majority of interrupted trans-Atlantic passenger flights (forced returns to the airport of departure or landing on islands) known from reports in the periodicals have also been due to various types of trouble in engines and their systems. In recent years, however, world aviation practice has experienced relatively fewer air disasters due to powerplant failure than it had in the past. This has been because the modern multiengined airplane has the ability to continue flight with partial and unbalanced thrust after failure of some of its engines. /8

Chapter I /9

PROBABILITY CHARACTERISTICS OF FLIGHT WITH PARTIAL AND UNBALANCED THRUST ON AIRCRAFT OF VARIOUS CONFIGURATIONS*

1. INFLUENCE OF TOTAL (n) AND CRITICAL (m) NUMBERS OF ENGINES ON THE PROBABILITY OF FORCED INTERRUPTION OF FLIGHT

As the number of engines in an airplane's powerplant increases, the probability of failure of one of them also naturally increases, other conditions the same.

On the other hand, the consequences of such failure become less dangerous: while engine failure on a single-engined airplane inevitably resulted in termination of the flight (i.e., at best a forced landing), the multiengined aircraft is capable of continuing in flight after failure of one or even more engines.

It is the interaction of the above two factors that determines the probability of the possible outcomes of partial powerplant failure on an airplane: forced termination of the flight or its continuation with partial and unbalanced thrust.

In practice, retention of the ability to continue level flight requires more than the existence of some single regime in which this requirement can be met. To be sure of horizontal-flight capabilities under real conditions, with execution of smooth heading changes, encounters with ordinary atmospheric disturbances, etc., it is necessary that there be a definite *range* of flight speeds without loss of altitude. The notion of the airplane's capability to continue level flight should be understood in this sense here and below.

The *probability of failure of an isolated engine*, designated /10
p, is the initial parameter in an analysis of the probability characteristics of aircraft flight with partial and unbalanced thrust.

Needless to say, in speaking of the ability or inability of an airplane to continue flight after failure of one or more engines, we are being somewhat arbitrary. Both "ability" and "inability" may manifest in different ways in similar situations.

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*In this case, we mean by the configuration of an airplane the total aggregate of the characteristics that determine its ability to perform level flight in the event of failure of one or more of the engines in its powerplant, namely: the number of engines, their placement, the airplane's power-to-weight ratio, its aerodynamic and weight characteristics, and even elements of equipment (for example, propeller-feathering devices).

When the engine of a single-engined aircraft fails, it descends at an angle whose tangent $\tan\theta = 1/K$, where K is the lift-drag ratio of the airplane in the particular configuration with consideration of the drag of the out engine. For most modern aircraft, with their characteristic high loads per unit wing area, this descent occurs at vertical velocities ranging into the tens of meters per second. As a result, forced landings, while possible, can be made only in the immediate vicinity of the point at which the engine failure occurred.

Even if it is not capable of continuing level flight on one engine,* a two-engined aircraft, on the other hand, can nevertheless use the thrust of the second, running engine after failure of the other, and thus descend, as a rule, at a moderate vertical velocity. If a certain altitude margin is available, the airplane can use it to reach, if not the nearest airport, at least the most suitable landing site, and there is enough time for the crew and passengers to prepare for the landing (or ditching). Consequently, although formally both of the aircraft named in this example have the same undesirable property – the inability to continue level flight with one engine out, the practical safety of the second one is obviously greater.

Note must also be taken of the fact that forced landings present different degrees of risk to the lives of the passengers and crew under different terrain conditions (flat country, woods, mountains, ocean, etc.). Such factors as the landing speed of the airplane, the design of its undercarriage, the strength of the cabin, and even the availability of seat belts and the positions of the passenger seats with respect to the direction of flight are also of no small importance here.

Consequently, the possibility or impossibility of continuing level flight after failure of a given number of engines cannot be regarded mechanically as a characteristic that defines flight safety fully. For example, equal safety ratings should not be /11 given to a light, slow-moving aircraft flying over level terrain and a main-line transoceanic aircraft, even if their inherent probabilities of forced termination of flight are equal.

Turning to the opposite property – the ability of an airplane to continue flight after failure of some of its engines – it must also be remembered here that this property may in practice manifest in different ways. Thus, it is most frequently possible to continue flight after failure of some engines only at an altitude considerably lower (as a rule, by several kilometers) than the normal cruising altitude.* As will be shown below (see Chapter III), a forced descent, although it does not in itself imply an immediate landing, is almost always detrimental to flight range and, consequently, may prevent the airplane from reaching its destination. It is easily understood that, let us say, in flights over the ocean, a forced descent is almost as bad as the prospect of terminating the flight immediately.

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*Use of such airplanes is regarded as unacceptable according to modern standards, but two-engined aircraft that were incapable of flight with one engine running did exist at earlier stages in the development of aviation.

In addition, it must be remembered that the probability of encountering clouds increases with the descent to a lower level; this may result in icing of the airplane, flight through zones of higher turbulence, and other phenomena that are just as pertinent from the standpoint of flight safety.

In 1936, when V.P. Chkalov was preparing for his flight from Moscow across the Arctic to the Far East, he was asked why he had chosen an ANT-25 single-engined airplane for this flight instead of a four-engined machine. His answer: "One engine means one hundred percent risk, and four engines four hundred percent." Strictly speaking, this response could be considered valid only if failure of a single engine on the four-engined airplane concerned would result in forced termination of the flight, which, generally speaking, did not follow from the characteristics of the machine. However, a subsequent event, the 1937 crash of the airplane in which S.A. Levanevskiy's crew attempted to fly from Moscow across the North Pole to America, showed that Chkalov's remark was valid for certain conditions. Failure of one engine on Levenevskiy's airplane forced a descent to lower altitude and continuation of the flight in clouds under icing conditions, which, to judge from available evidence, were the most probable cause of the disaster.

Thus, consideration of the "ability" or "inability" of an airplane to continue flight after failure of some engines in isolation from the conditions under which the flight is being made does not give a complete answer to the question posed. /12

Nevertheless, in order to obtain at least a first-approximation basis for quantitative comparison of aircraft with different configurations from the standpoint of flight safety in the case of interest to us, it is expedient, even with consideration of all of the reservations stated above, to take as our basic defining parameter the probability of forced termination of the flight P_{tm} due to partial powerplant failure at a given probability p of failure of an isolated engine with its accessory systems. This last quantity can be established from statistical data for a given type of engine. It will usually be referred to a certain number of flight hours logged. Here we mean by failure of an isolated engine or systems thereof (fuel, lubrication, etc.) in cruising flight a malfunction that makes it impossible to obtain the thrust (power) necessary for flight from the engine and one that cannot be corrected in flight.

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*This rule has exceptions in the comparatively rare cases in which the cruising speed is determined not by the output capability of the powerplant (available excess power), but by other circumstances, e.g., passenger cabin pressurization conditions. One of these exceptions may be found in the Be-30 airplane, which is capable of flying at the cruising altitude established for it with one engine running.

The possibility of quantitative estimation of the probability of forced termination of flight owing to failure of some engines at a stated probability of isolated-engine failure for aircraft of different design layouts and dynamic data (total number of engines, ability to continue flight after failure of some of them) would be highly useful in aircraft design, preparation of tactical-technical specifications, selection of hardware for performance of specific functions, appraisal of the readiness of a newly acquired airplane for passenger hauling, and in a number of other cases in the production and operation of aircraft.

Let us assume that n engines are mounted on an airplane, that the probability of failure of each of them is p, and that no fewer than m engines must fail to render the airplane incapable of continuing level flight.

In other words, flight is no longer possible on (n - m) engines, but it is still possible on (n - m + 1) engines.

Then the probability P_{tm} that the airplane will be unable to complete a flight successfully will equal the probability of failure of m engines out of n.

Strictly speaking, we should also add to this the probability of failure of (m + 1) engines, (m + 2), and so forth up to and including the probability of failure of all n engines, since in any of these cases continuation of the flight would be the more impossible. However, the sum of the probabilities of all these cases is very small (it is proportional to higher powers of p) compared with the probability of failure of m engines and can be left out of account with no detriment to the practical accuracy of the calculations.

Here it is assumed that all of the engines on the airplane are mutually independent, i.e., that failure of one of them does not depend on the good working order of the others and, in turn, does not influence their performance. In the overwhelming majority of cases, this assumption is realistic; the known exceptions will be discussed separately. /13

According to the Bernoulli formula, the probability of failure of m engines out of n is

$$P_{\mathrm{tm}} = \overset{m}{\underset{n}{C}}\, p^{m} (1 - p)^{n-m},$$

where $\overset{m}{\underset{n}{C}}$ is the number of possible combinations of m elements taken n at a time, which, as we know, equals

$$\frac{n!}{m!\,(n - m)!}.$$

Or, recognizing that the higher powers of p, beginning with (m + 1), can be rejected,

$$P_{\mathrm{tm}} = \overset{m}{\underset{n}{C}}\, p^{m}. \qquad (1)$$

This formula enables us to determine the probabilities of forced termination of flight, P_{tm}, for the basic design layouts of modern aircraft as functions of the reliability of the engines mounted on them (see Table 1).

Figure 1 represents the $P_{\mathrm{tm}}(p)$ relation graphically for various n and m.

Here the values of P_{tm} are plotted against the axis of ordinates on a logarithmic scale, since the absolute values that they take for the various relationships of n to m differ from one another quite substantially — by factors in the hundreds, thousands, and tens of thousands. There is no doubt that such substantial differences greatly reduce the importance of the reservations stated above as to the need for applying qualitative corrections to the results obtained by the proposed method. Even when these corrections are taken into account, the difference in the degrees of flight safety for aircraft of different configurations on partial failure of their powerplants remains striking.

The effect of changes in the argument itself — the probability of isolated-engine failure — is also comparatively small against the background of such relationships. For this reason, the possible inaccuracies of available information on the importance of the latter may also be without any substantial influence on the results of a flight-safety comparison made between aircraft having different total and, most importantly, critical numbers of

TABLE 1. PROBABILITY OF FORCED TERMINATION OF FLIGHT AS A RESULT OF FAILURE OF ENGINES ON VARIOUS TYPES OF AIRCRAFT

Description of airplane	Total number of engines, n	Critical number of engines, m	Probability of forced termination of flight, P_{tm}
Single-engined	1	1	p
Two-engined, incapable of flight with one engine running	2	1	$2p$
Two-engined, capable of flight with one engine running	2	2	p^2
Three-engined, capable of flight with no fewer than two engines running	3	2	$3p^2$
Three-engined, capable of flight with one engine running	3	3	p^3
Four-engined, capable of flight with no fewer than three engines running	4	2	$6p^2$
Four-engined, capable of flight with no fewer than two engines running	4	3	$4p^3$

engines. This last remark is of no small importance, since it is precisely the practical worker who need not expect fully accurate data characterizing the reliability of the isolated engine, and especially that of new models, which are of the greatest interest from the standpoint of estimating the probable degree of flight safety. /14

We see from Fig. 1 that if a four-engined airplane is capable of continuing flight after failure of two engines, its probability of forced termination will, other conditions the same, differ by a factor 4p from the corresponding probability for a two-engined airplane capable of flying on one engine. For realistic values of p, this corresponds to a sharp increase in safety; thus, if we take $p = 10^{-5}$, the probability P_{tm} for this four-engined airplane will be only $4 \cdot 10^{-5}$ of that for such a two-engined airplane. As p increases further, this difference becomes still more appreciable. However, if the four-engined airplane were capable of continuing flight only after failure of no more than one engine,

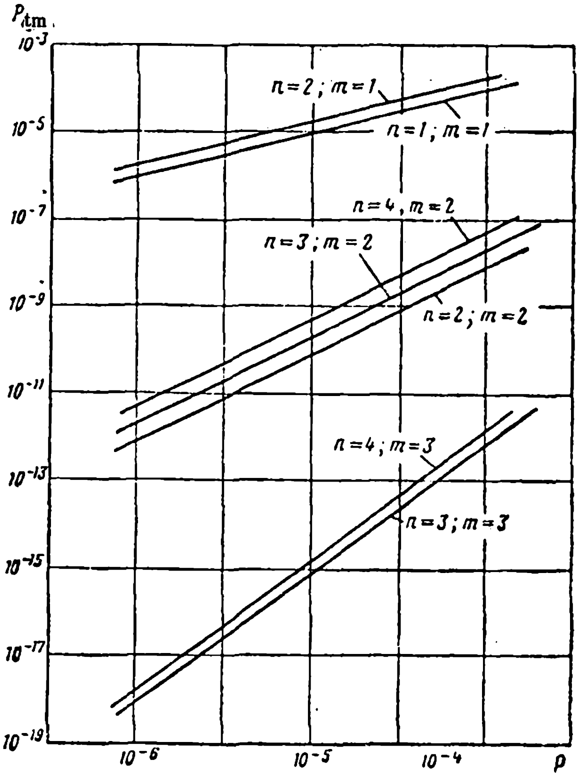

Figure 1. Probability P_{tm} of Forced Termination of Flight Due to Partial Powerplant Failure as a Function of the Probability (p) of Failure of an Isolated Engine for Aircraft with Various Total (n) and Critical (m) Numbers of Engines.

its reliability would be substantially (by a factor of 6) inferior to the reliability of the two-engined airplane capable of flying on one engine.

Thus, the critical number of engines m is the principal decisive factor in determining flight safety after partial powerplant failure. /15

The influence of all other factors, including even p, which characterizes the reliability of the isolated engine, is incomparably smaller.

And, for this reason, it is necessary in finalizing new hardware and placing it in operation to give first attention to those design and equipment elements of the airplane whose proper functioning determines the critical number m. Herein lies the key to improvement of the operating safety of the airplane as a whole.

As an example of such an element, we might refer to the propeller-feathering system of a four-engined turboprop airplane. When the propellers of engines that have failed are feathered, such an airplane is, as a rule, capable of continuing flight even after failure of two out of the four engines. As we indicated above, this lowers the probability of forced termination of the flight by a large factor compared with the probability of termination of a two-engined airplane capable of flight on one engine – the classical configuration of the recent past (assuming, of course, that their engines are equally reliable). But it is only necessary for the feathering system to fail to render the four-engined turboprop airplane hardly capable of continuing flight after failure of only one engine, and its inherent flight safety is no longer better, but several times worse than that of the two-engined airplane. In other words, a decrease /16 in the number* m in this case has the effect of transferring the airplane from one safety category to another, lower one. And, paradox though it may seem, we find that reliability of the feathering system is more important for flight safety than even the reliability of the engines themselves!

It is for this reason that doubly and triply redundant feathering systems are used on all modern turboprop-engined aircraft.

On the other hand, the presently observed tendency toward substantially longer times-to-overhaul of aircraft engines (up to several thousand engine hours), which is extremely important from the standpoint of air-transport economy, has unquestionably become possible not only because the engines themselves have been made more reliable, but also because the modern multiengined aircraft is capable of continuing flight in safety after failure of some of its engines.

In essence, we have here a manifestation of a general trend that is characteristic for modern reliability theory — the development of systems whose reliabilities are considerably greater than those of the elements of which they are composed.

In fact, as we see from Fig. 1, the same probability of forced termination of flight in aircraft with different total and critical numbers of engines corresponds to substantially different reliability values for the isolated engine. This fact might be of interest, for example, when new aircraft types are being placed in service and their use in routine operations hinges on their attainment of a general reliability level no poorer than that of the aircraft already in service (although the engines on the new aircraft may not have been brought up to the same reliability level as the engines on the aircraft in use).

Analysis of the curves in Fig. 1 shows that the requirement sometimes made of aircraft according to which they must be capable of continuing level flight for an extended time after failure of a stated fraction of the total number of engines (e.g., 50%) does not altogether accurately characterize the comparative degrees of safety of different aircraft in this case. Failure of one engine of a two-engined airplane (50% of the powerplant) is considerably more probable than failure of two engines of a four-engined aircraft (the same 50%).

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*It should be remembered that the critical number m, unlike the total number of engines n, is not forever inherent to an airplane of a given type. On the same airplane, it may vary as a function of flight weight (burnoff of fuel, payload), undercarriage and wing-flap positions, and other similar factors.

In other words, an increase in m increases flight safety to a much greater degree than an increase in n lowers it.

We noted above that in some cases, failure of one of the engines may result in failure, self-shutdown (for example, as a result of severe surging or disturbances to the normal motion of air at the intake), or forced shutdown (for example, in the event of fire) of a neighboring or several neighboring engines, which, naturally, it would be inappropriate to regard as isolated in such a situation. Practice has even witnessed cases in which a broken compressor blade thrown by one engine was inducted into the air intake of the engine beside it, putting it out of service [20].

In analyzing the probability of such cases, it is convenient to consider the combination of several engines whose mutual effects on one another are not excluded as a single unit. The solution of a closely related problem was given by V.I. Siforov in application to electronic systems [16].

There is reason to expect that the problem of the reciprocal effects of engine failures will become substantially more urgent with the advent of VTOL and STOL aircraft in which it is proposed to use a large number of compactly spaced lifting engines.

Clustering of engines is relatively seldom encountered among the aircraft presently in service. A set of measures designed to ensure a high degree of functioning independence among the neighboring engines is therefore specially designed into such aircraft and tested in flight tests: separation of the air streams at the intakes, fire-resistant insulation, independent control, fuel-supply, and lubricating systems, etc. As a result, the assumption /18 made above to the effect that random failures of engines on modern, thoroughly refined and finalized aircraft are mutually indepedent may be regarded as practically acceptable.

2. PROBABILITY OF FLIGHT WITH PARTIAL AND UNBALANCED THRUST

Thus, the trend to larger critical numbers of engines that is characteristic for present-day aircraft design is highly favorable from the standpoint of safety. But it also inevitably involves at the same time an increase in the total number of engines forming the airplane's powerplant, with the result that there is also an increase in the probability P_1 of partial-thrust flight itself, which represents the sum of the failure probabilities of x engines out of n, where $1 \leq x \leq (m - 1)$:

$$P_1 = \sum_{x=1}^{x=m-1} \overset{x}{\underset{n}{C}} p^x,$$

or, recognizing the smallness of the subsequent terms of the series as compared with the first,

$$P_1 \cong np. \qquad (2)$$

Needless to say, this formula is not applicable to the single-engined airplane or to the two-engined airplane that is incapable of flight with one engine running, since in these cases partial-thrust flight is totally impossible ($P_1 = 0$).

For all other airplanes, however, the probability of flight with partial thrust increases in direct proportion to the number of engines that they carry.

The probability P_2 of flight with unbalanced thrust for a two-engined airplane capable of continuing flight on one engine is naturally equal to its probability of flight with partial thrust.

For a four-engined airplane capable of flying on two engines, the probability of flight with unbalanced thrust will be somewhat lower than that of only partial thrust. When one engine fails, partial-thrust flight will necessarily be at the same time unbalanced. However, when two engines fail (which is highly improbable, but still not totally excluded), cases of both unbalanced and balanced thrust are possible, depending on the positions of the running and nonrunning engines. Denoting the possible combinations of running engines (by their numbers from one outboard end to the other) 1 + 2, 1 + 3, 1 + 4, 2 + 3, 2 + 4, 3 + 4, it is easily seen that only one-third of the indicated possible combinations (those underscored) correspond to flight with balanced thrust, and the other two-thirds to unbalanced-thrust flight. True, the degree of imbalance when the two engines on one wing /19
remain running will differ substantially from the imbalance when the running engines are the outboard engine on one wing and the inboard engine on the other.

However, as was shown above, the probability of failure of two engines on the same flight is so much lower than that of failure of a single engine that it is quite admissible to disregard the possibility altogether, the more so since only 2/3 of the possible combinations in double engine failure result in unbalanced thrust. We may therefore assume that even for a four-engined airplane

$$P_2 \cong P_1 \cong np.$$

The situation is somewhat different with the three-engined airplane. If it is capable of flight after failure of only one of its engines, the probability of unbalanced-thrust flight will be $P_2 = 2/3np = 2p$, i.e., it will correspond to the probability of failure of one of the lateral engines.

If, however, the same airplane can continue flight after failure of two engines, a second term is added to the above quantity to reflect the probability of failure of one of the lateral engines in combination with failure of the central engine. But here again, since the cofactor p^2 appears in this second term, it can be dropped without practical detriment to calculation accuracy.

Thus, the general formula for rough estimation of the probability of flight of an airplane of one of the modern configurations with unbalanced thrust will be

$$P_2 = n'p, \qquad (3)$$

where n' is the number of engines mounted on the airplane outside its plane of symmetry.

This circumstance cannot but be regarded as another positive property of aircraft having at least one of the engines situated in the plane of symmetry, and of three-engined aircraft in particular.

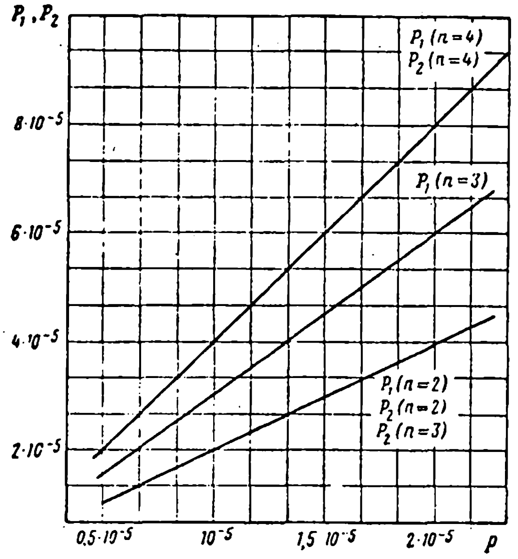

Figure 2. Probabilities of Flight with Partial (P_1) and Unbalanced (P_2) Thrust as Functions of the Probability p of Failure of an Isolated Engine for Aircraft with Various Number of Engines n.

Figure 2 indicates the probabilities of flight with partial and unbalanced thrust as they depend on the probability of isolated-engine failure for aircraft with several of the configurations most commonly encountered at the present time. We see from comparison of Figs. 1 and 2 that the safest aircraft (from the viewpoint of the possibility of continued flight after failure of some engines) have, at the same time, the highest probabilities of flight with partial and unbalanced thrust.

At the present reliability level of aviation engines, the probability of flight with partial and unbalanced thrust is in all cases several orders higher /20 than the probability of forced termination of the flight.

This circumstance, which is characteristic for contemporary aviation, calls urgently for study of the dynamics of the flight of modern two- and multiengined aircraft with partial and unbalanced thrust and piloting techniques and plotting methods for such flight.

In speaking of the probability characteristics of flight with partial and unbalanced thrust, it must be remembered that the statistical probabilities of failure of an engine of a given type are usually related to a definite number of logged engine hours. If it is necessary to find the probabilities P_{tm}, P_1, or P_2 referred to some other parameter, e.g., passenger-kilometers, it is first necessary to convert the corresponding starting value of p by multiplying it by the correction coefficient

$$b = \frac{1}{TVi},$$

where T is the time to which the initial failure probability p of an engine of the particular type is referred, in hours; V is the flight speed (average) of the particular type of aircraft, in km/h; i is the number of passengers. /21

The results of this conversion indicate that, other conditions the same, modern high-speed multipassenger aircraft are relatively safer than the slow aircraft of the recent past, which were designed for small numbers of passengers.

Chapter II /22

DIVERGENT MOTION OF THE AIRCRAFT AFTER LOSS OF THRUST SYMMETRY

1. MOMENT OF UNBALANCED THRUST. PILOT REACTION

Failure of an engine located outside the airplane's plane of symmetry gives rise to an unbalanced-thrust moment $M_{u.t}$ that tends to turn the airplane around its vertical axis as shown schematically in Fig. 3.

The magnitude of the unbalanced-thrust moment is equal to the product of the distance z from the line of action of the failed engine's thrust to the center of gravity of the airplane times the sum of the thrust P of the engine positioned symmetrically with respect to the out engine plus the drag Q_{en} of the out engine:

$$M_{u.t}=Pz+Q_{en}z=(P+Q_{en})z.$$

In practice, the aerodynamic drag Q_{en} of the out engine sometimes reaches values neglect of which would result in calculated values of the moment $M_{u.t}$ substantially lower than the actual ones.

Thus, the total aerodynamic drag of an airplane having two turbojet engines may increase to 125-130% of its original value in normal flight with balanced thrust when the airplane flies on one engine [19].

The basic cause of this additional drag is autorotation of the out engine. Consequently, the drag Q_{en} depends on the autorotation speed.

On propeller aircraft, the autorotation or windmilling rpm are substantially higher than on aircraft with turbojet or turbofan engines because the propeller governor always adjusts propeller pitch (in the range between stops) in such a way as to preserve the original rpm.

The drag of an autorotating turboprop engine is especially large, and may even exceed the rated thrust of a running engine of the same type. The physical causes of this effect and methods of overcoming it will be the subjects of a special discussion (in Sec. 6 of this chapter). /23

Since the basic cause of the additional drag Q_{en} of the out engine is its autorotation, it is necessary to establish the source from which the energy necessary to drive the autorotation is drawn in order to understand the essence of the phenomenon. It is easily shown that the energy of the oncoming air stream is the only such source. However, this draft on the available energy inevitably results in further deceleration of the stream and, as a consequence, a corresponding increase in aerodynamic drag. To overcome the additional drag that has appeared, it is necessary either to increase the thrust of the remaining working engines or to use the longitudinal component of the airplane's weight, i.e., to go from level to descending flight (or from a climb to level flight). However, these measures cannot be taken instantaneously, immediately after failure of one of the engines. Subsequent compensation for the thrust missing in such a situation will be considered later (see Chapter III). However, in analyzing the divergent motion of the airplane during the first few seconds after failure of a lateral engine, we should begin from the fact that the effects of both the imbalance and, in particular, the deficiency of thrust are practically uncompensated during these first few seconds by any deliberate action of the pilot.

The reason for this is that the reaction of a human to a change in his external situation occurs not instantaneously, but after a certain time has elapsed, in accordance with natural physiological laws.

It has been established that the length of this interval, which is known as the reaction time or simply the reaction, varies over a rather broad range under the influence of a number of factors.

Thus, Z. Gerathewohl [5] notes that "...even under ideal conditions, the human reaction time is approximately 0.1 sec, but in most cases encountered in everyday life, a considerably longer time elapses between the signal and the

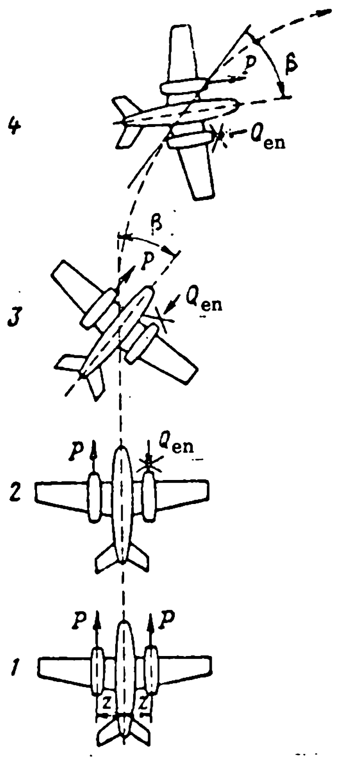

Figure 3. Diagram Showing Turn Executed by Airplane Under the Action of an Unbalanced-Thrust moment $M_{u.t}$: 1) Straight-line flight with symmetrical thrust; 2) failure of one engine, $M_{u.t} = (P + Q_{en})z$; 3) rotation of airplane's axis of symmetry under the action of the unbalanced-thrust moment (the trajectory remains rectilinear on inertia); 4) trajectory of motion deflects as a result of rotation of the airplane's symmetry axis.

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response that it triggers." Here, according to Gerathewohl, the reaction time depends strongly on the nature of the stimulus. Thus, under the ideal laboratory conditions referred to above, the average reaction times were:

0.09-0.19 sec for tactile stimuli,

0.12-0.18 sec for auditory stimuli, and

0.15-0.22 sec for visual stimuli.

It is interesting to note that from the standpoint of speed, the visual information channel was found to be far from the best; nevertheless, it is the principal channel in determining human activity in the "pilot-airplane" system because of a number of its other advantages (volume of information, detail, clarity, etc.).

Under real conditions, human reaction time is influenced by such factors as the complexity of the required reaction, surprise, the degree of danger (real or imagined) presented by the external disturbance, and many others. As a result, the reaction time may be increased to several seconds.

In this case, definite importance attaches to the natural traits of the individual. Some people are known to have a tendency to slower or faster reactions. The physiological condition of the individual at the particular time is of no small importance.

Under the influence of conditioning – general conditioning aimed at developing fast reactions in general or specific conditioning limited to the refinement of certain operations – reaction times may be substantially reduced (sometimes to a fraction).

In this case, therefore, the subjective factors characterizing the individual are of great importance. However, the objective conditions under which this reaction is to take place are nevertheless found to have the strongest influence on human reaction time.

Foremost among these circumstances are the unexpectedness of the phenomena requiring a certain response reaction on the part of the human and the complexity of this reaction. For example, the reaction delay of a normal healthy individual normally does not exceed 0.15-0.20 sec in such a classical psychophysiological experiment as the one in which a button is pressed in response to the lighting of a lamp. However, it is only necessary to complicate the experiment slightly, for example, by requiring that the button /25 be pressed only when a lamp of a certain color lights up, to increase the time of the more complicated reaction to 0.5-0.6 sec. The need to choose, evaluate, and take a decision involves additional time.

The reaction to occurrences that are rare (and, consequently, improbable at any given time) is even more complex and hence slower, the more so if it is at the same time not without bearing on the safety of the individual whose reaction is being investigated (it will be observed without prompting that these last two conditions — unexpectedness and the possibility of danger — are fully consistent with engine failure in flight). Special experiments have shown that a reaction requiring the perception and evaluation of phenomena that are unexpected and, in addition, dangerous for the individual and determination of both the basic expediency of response actions and the nature of these actions is inevitably protracted in time to several times the figure for a simple reaction (of the "lamp-button" type).

It has been observed in certain studies of pilot handling of aircraft that the pilot's time to react to engine failure may be further extended because the pilot is not immediately aware of the very fact that the failure has occurred.

Thus, N.V. Lebedev [9] pointed out that "an inexperienced pilot manages to detect an engine failure quickly in far from all cases, since it is difficult for him to detect it by ear in his sealed cabin enclosure with his headset on and tightly covering his ears. Not even the tachometer advises him of engine failure at once, since the propeller governor...continues to hold revolutions constant. There may be no outward signs of changes in engine performance, such as popping from the exhaust pipes, smoke or vapor from under the cowling, an increase in the vibration of one engine as compared to the others, etc., and if there are, the pilot does not always turn his attention to them at once." The above remarks were made with propeller aircraft in mind, but they are also fully applicable to aircraft with gas-turbine engines.

The only exception to be taken to Lebedev's statement is that the pilot has essentially the task of reacting not so much to the very fact of engine failure as to the consequence of this fact, i.e., the divergent motion of the airplane (in particular, the drop off onto one wing), which it is impossible not to notice in the overwhelming majority of cases. For this reason, it is now the convention to define the instant of engine failure as the instant at which the decrease in its thrust becomes noticeable in the behavior of the airplane or from instrument readings.

True, there have also been cases in which the pilot noticed /26 neither the failure of the engine nor the subsequent divergent motion of the airplane. While taking off in a heavy strategic jet bomber with four engines mounted in the root section of the wing in close proximity to the fuselage, one highly experienced pilot did not notice failure of one of the engines on the last third of the takeoff run. This is easily explainable: to determine by ear from a cabin far up in the nose of the airplane whether four or three engines are running is difficult; the wide range of takeoff weights at which the particular airplane was flown had made it difficult for the pilot to accustom himself to any definite takeoff distance; but the principal and no doubt decisive factor was that aircraft of this configuration are not subject to substantial unbalanced-thrust moments on failure of one engine. Hence the tendency of the airplane to yaw and drop off to the side was so weak that the pilot did not distinguish it from the external disturbances, as a signal against the noise background, and countered it easily by a small reflex deflection of the controls.

However, when engine failure results in a pronounced divergent lateral motion of the airplane, the first thing required of the pilot is, as will be shown below, that he counter the motion independently of analysis of its causes.

However, since the pilot's reaction cannot be instantaneous even when his actions are patterned in this way, it is customary to regard the divergent motion of the airplane during the first few seconds (usually five) after failure of a lateral engine as an uncontrolled motion taking place without intervention by the pilot.

This assumption is expedient not only because it corresponds quite closely to the actual state of affairs and reflects a situation that is possible in practice, but also because examination of the characteristics of the airplane's uncontrolled divergent motion during a given time interval after failure of a lateral engine makes it possible to evaluate its behavior objectively in this extremely important case of flight and to determine the conformity (or nonconformity) of this behavior to the established standards.

In practice, the aerodynamic characteristics of an airplane are not always sufficiently effective to ensure acceptable uncontrolled-motion parameters in such cases. The most efficient way to overcome this deficiency is to provide the control systems of modern aircraft with automatic devices that ensure a sharp increase in the damping of the divergent motion or even active countering of that motion (automatic piloting). However, the incorporation of automating elements into control systems is so widely practiced in contemporary aircraft design that there is no basis for linking it exclusively to the dynamics of the airplane with an unbalanced thrust deficiency. However, there is no doubt that the operation of the automatic stabilizing devices will make itself especially strongly felt in precisely this case, which is one of the most complex encountered in flight practice. In particular, it should be noted that such devices, which are capable of responding much faster than a man, provide correspondingly more timely intervention in control on failure of a lateral engine. Here the probable delay time is no longer five seconds, but at least one order shorter. As a result, the amplitude of the divergent motion, especially in roll, is also found to be significantly smaller, and /27 relatively less energetic activity on the part of the pilot is required to counter it. Damping devices that operate independently of one another in all three basic channels — pitch, yaw, and roll — are installed on most modern airplanes. The last two channels are especially important for aircraft whose engines are positioned far outside the plane of symmetry.

Failure of one engine, irrespective of the number of engines on the airplane, is usually taken as the basic theoretical case for analysis of divergent motion under the action of unbalanced thrust. This assumption must also be recognized as quite sound. The failure probability of a modern engine is extremely low in the first place, and even if we assume the possibility of failure of a second engine or even more engines on the same flight independently of the first, such a failure could, in any event, occur only when the divergent motion of the airplane caused by failure of the first engine has already been brought under control. On the other hand, simultaneous failure of two mutually independent engines should be regarded as practically improbable for aircraft with modern configurations. Provision must obviously be made for this possibility on VTOL aircraft, which may carry 12, 16, 20 or more lifting engines, whose very number, together with the relatively short running times characteristic for them, will evidently require a new approach to estimation of the probability of a subsequent engine failure before the divergent motion caused by the preceding failure has been steadied.

2. SLIP CAUSED BY FAILURE OF A LATERAL ENGINE AND ITS INFLUENCE ON THE MOTION OF THE AIRPLANE

Under the action of an unbalanced-thrust moment, an airplane turns about its vertical axis; this also turns the line of action of the thrust of the running engines. However, the trajectory of the airplane's motion cannot rotate instantaneously, with no time lag, together with the longitudinal axis of the airplane and the line of thrust action. The inertia inherent to the airplane, as /28
to any material body possessing mass, tends to resist this rotation. As a result, the trajectory turns with a definite time lag behind the rotation of the airplane's longitudinal axis. As a result, an angle of slip β forms between the airplane's plane of symmetry and the direction of its motion (velocity vector), as is shown schematically in Fig. 3.

If the motion of the airplane under the action of the moment $M_{u.t}$ is not subsequently counteracted, the angle of slip will tend to a certain value β_1 at which equilibrium is established between the unbalanced-thrust moment and the restoring weathercock moment $M_y^{\beta}\beta$ that naturally arises during slip (Fig. 4):

$$M_{u.t}+M_y^{\beta}\beta=0.$$

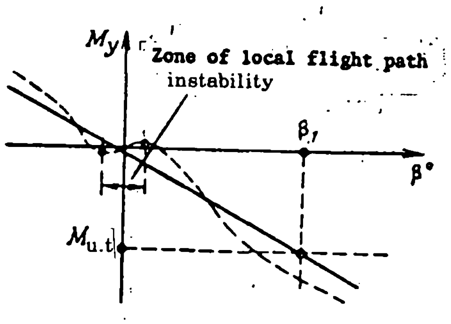

Figure 4. Illustrating the Notion of the Equilibrium Angle of Slip.

The angle of slip that can be attained in uncontrolled motion of an airplane under the action of an unbalanced-thrust moment varies in very broad limits depending on the airplane's flight path stability, its thrust-weight ratio (i.e., the relative thrust of the engine symmetrical with respect to the one that has failed), the drag of the failed engine, and especially the offset of the engines relative to the plane of symmetry. On existing aircraft, this last quantity varies in a very broad range and, naturally, other conditions the same, the failure of engines on the aircraft shown as examples in Figs. 5 and 6 will give rise to unbalanced-thrust moments that differ from one another in proportion to the offset of these engines.

In view of the possibility of the airplane's assuming rather large angles of slip in this case (upwards of ten degrees), it would be desirable to have at least a qualitative estimate of the danger presented by this slip and the precise nature of its manifestations.

Slip may be dangerous in two respects.

Firstly, detachment of the flow past the vertical tailplane, and sometimes even reversal of the rudder, may occur at large angles of slip, with the result that the restoring moment of flight path stability drops sharply, the angle of slip increases even further, and the airplane turns on its trajectory through an angle such that /29 the flow also detaches from the wing, possibly stalling the airplane. It is customary to consider that stalling is due to pitch-up to angles of attack larger than critical. This is the case in most instances of practical flying. For example, large angles of slip have a strong influence on the critical (detachment) angle of attack, tending to make it smaller (Fig. 7). However, the possibility of stalling directly as a result of assumption of large angles of slip cannot be excluded in certain cases. These situations include, as we know, the loss of flight path stability by aircraft flying at high supersonic speeds ($M > 2.5$-3).

However, in the range of normal cruising Mach numbers, yaw to the angles of slip at which the flow may separate from the vertical tailplane is improbable.

The second and, as has been shown by practice, most immediate and therefore most real danger associated with slip consists in the appearance of divergent motion not only in the flight path plane, but also /30 in the transverse plane, i.e., banking of the airplane. Many types of aircraft do not yaw as strongly as they roll in the direction of the out engine. Characteristically, it is precisely the amount of roll that occurs during a predetermined time interval (usually 5 sec) after engine failure without pilot intervention, rather than any other parameter, that is taken as a criterion in evaluating the actual parameters of an airplane's motion after failure of a lateral engine.

It may seem strange at first glance that the application of an external moment in the yaw plane causes the airplane to respond principally in the transverse plane, in which no external disturbances are acting. The explanation is to be sought in the laws governing the influence of lateral static stability on the motion of an airplane, of which we shall speak in greater detail below (see Sec. 4 of this chapter). The two components of this stability – transverse and directional – are closely related to one another and, as a rule, manifested together. /31

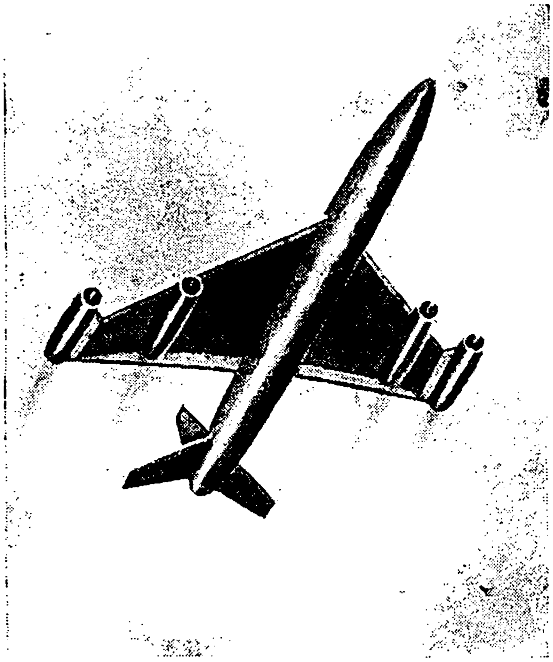

Figure 5. Airplane with Outboard Engines Mounted Far Outside the Plane of Symmetry.

Therefore, despite the fact that the external disturbance in our case acts only in the yaw plane, the airplane responds to it with a combined lateral motion about two axes: x and y.

Strictly speaking, slip also has a certain influence on the aerodynamic moments acting in the third (pitch) plane. In most cases, however, this effect is relatively minor. Aircraft with the now quite common T-shaped tails, which develop a pronounced pitchdown moment during slip, are an exception. From the standpoint of lowering the stall probability, this phenomenon must be regarded as favorable: in the presence of slip, the airplane tends to drop its nose and go to smaller angles of attack (this will be recognized as especially important in light of the characteristic dependence of α_{cr} itself on β as indicated in Fig. 7).

However, we must not overlook the fact that, for example, in the landing approach, the pitchdown moment due to slip adds to the moment of the same sign that usually arises when the wing flaps

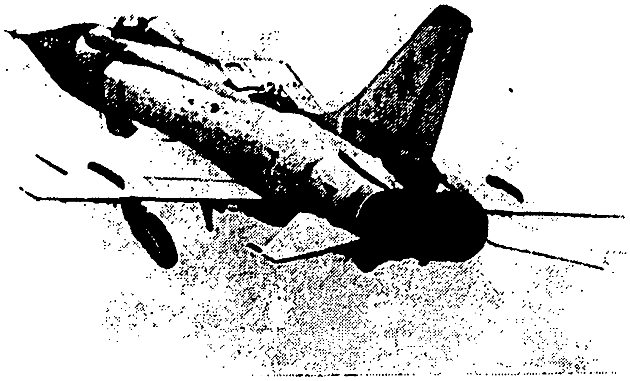

Figure 6. Airplane with Engines Situated Near the Plane of Symmetry.

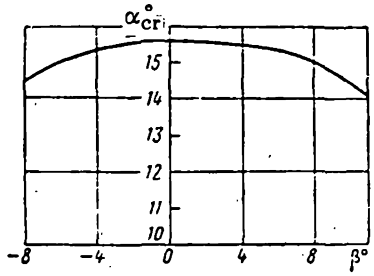

Figure 7. Influence of Slip on Critical Angle of Attack.

are in position for landing. As a result, the margin of elevator deflection necessary to level out and land may be reduced considerably.

3. EQUATIONS OF THE AIRPLANE'S LATERAL DIVERGENT MOTION

The equations of the lateral divergent motion represent particular cases of the general system of differential equations of motion of the airplane for the conditions V = const, α = const, ϑ = = const, and ω_z = const, and take the form

$$\left.\begin{aligned} m\left(\frac{dV_z}{dt}+\omega_x V_y-\omega_y V_x\right)&=Z+G\cos\vartheta\sin\gamma;\\ J_x\frac{d\omega_x}{dt}&=\sum M_x;\\ J_y\frac{d\omega_y}{dt}&=\sum M_y;\\ \frac{d\gamma}{dt}&=\omega_x-\omega_y\cos\gamma\,\mathrm{tg}\,\vartheta, \end{aligned}\right\} \quad (4)$$

where J_x and J_y are the moments of inertia of the airplane
ω_x, ω_y and ω_z are the angular velocities
M_x and M_y are the external-force moments
about the corresponding axes;
γ is the angle of roll and ϑ is the angle of pitch.

Transforming this equation system with consideration of the fact that β, γ, ω_y, and ω_z are small, we obtain /32

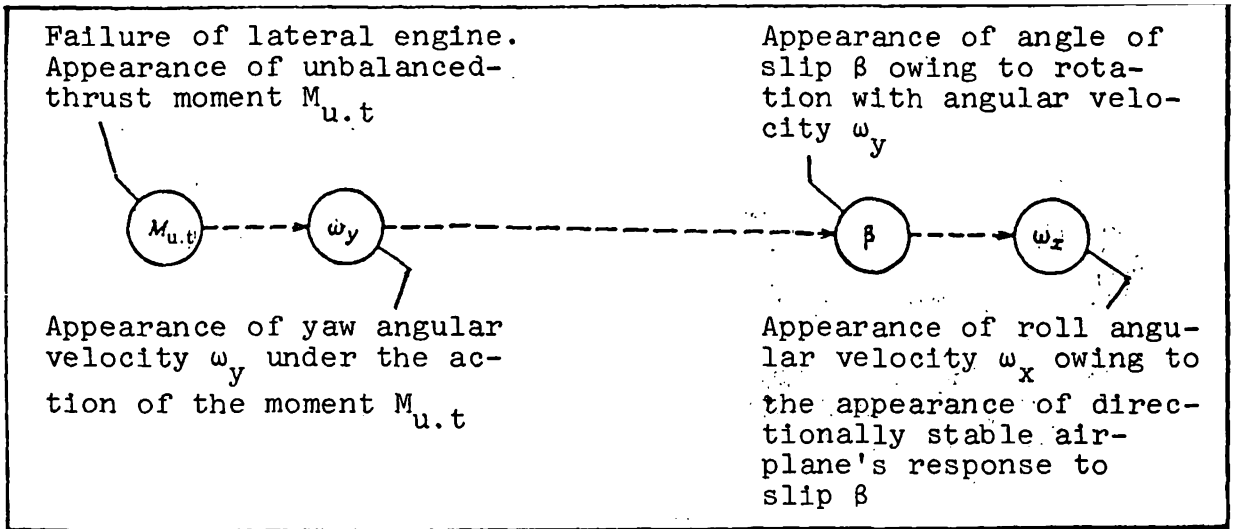
Failure of lateral engine. Appearance of unbalanced-thrust moment $M_{u.t}$
Appearance of angle of slip β owing to rotation with angular velocity ω_y
$M_{u.t}$
ω_y
β
ω_x
Appearance of yaw angular velocity ω_y under the action of the moment $M_{u.t}$
Appearance of roll angular velocity ω_x owing to the appearance of directionally stable airplane's response to slip β

Fig. 8. Illustrating Sequence of Phenomena Accompanying Divergent Motion of Airplane Under Action of Unbalanced-Thrust Moment.

$$\left.\begin{aligned}
&\frac{d\beta}{dt}=\frac{Z^{\beta}}{mV}\beta+\omega_x\sin\alpha+\omega_y\cos\alpha+\frac{G\gamma\cos\vartheta}{mV};\\
&\frac{d\omega_x}{dt}=\frac{M_x^{\beta}}{J_x}\beta+\frac{M_x^{\omega_x}}{J_x}\omega_x+\frac{M_x^{\omega_y}}{J_x}\omega_y;\\
&\frac{d\omega_y}{dt}=\frac{M_y^{\beta}}{J_y}\beta+\frac{M_y^{\omega_x}}{J_y}\omega_x+\frac{M_y^{\omega_y}}{J_y}+\frac{M_{\text{н.т}}}{J_y};\\
&\frac{d\gamma}{dt}=\omega_x-\omega_y\,\mathrm{tg}\,\vartheta.
\end{aligned}\right\} \qquad (5)$$

To obtain results of most general form from analysis of the lateral stability of a given airplane under these conditions, to determine the nature of the divergent lateral motion (oscillatory or spiral) and the rate at which it is damped, equation system (5) is subjected to further transformations: it is reduced to dimensionless form and the roots of the characteristic equation corresponding to particular solutions of the system are analyzed. The solution of Eqs. (5) enables us to compute both the free motion of the airplane that arises under the action of an instantaneous disturbance and the motion of the airplane due to the unbalanced-thrust moment.*

Figure 8 is a schematic representation of the physical pattern of the airplane's motion after failure of a lateral engine.

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*See, for example, [10].

It should not, of course, be concluded that the phenomena reflected in this diagram are developed one after another — that a certain steady angle of slip is reached first, then the angle of roll begins to increase, etc. In reality, the variations of all these parameters are interrelated in complex fashion, with very small anticipation of any one by others. /33

The purpose of the diagram is to indicate the basic direction of the cause-and-effect relations between the phenomena affecting the airplane after an unbalanced powerplant failure.

As we see from Eqs. (5), the derivatives linking the moments M_x and M_y and the force Z to the angle of slip β and the angular velocities ω_x and ω_y figure prominently in (5) among the quantities influencing the time variation of the angles of slip and roll and the roll and yaw angular velocities in addition to the perturbing moment $M_{u.t}$:

$$Z^{\beta}=\frac{\partial Z}{\partial \beta};\quad M_x^{\beta}=\frac{\partial M_x}{\partial \beta};\quad M_y^{\beta}=\frac{\partial M_y}{\partial \beta};\quad M_x^{\omega_x}=\frac{\partial M_x}{\partial \omega_x};$$

$$M_x^{\omega_y}=\frac{\partial M_x}{\partial \omega_y};\quad M_y^{\omega_x}=\frac{\partial M_y}{\partial \omega_x};\quad M_y^{\omega_y}=\frac{\partial M_y}{\partial \omega_y},$$

where

$$Z=c_z S\frac{\varrho V^2}{2};\quad M_x=m_x Sl\frac{\varrho V^2}{2};\quad M_y=m_y Sl\frac{\varrho V^2}{2}.$$

Thus, we find that the lateral motion of the airplane in response to the given external disturbance is determined primarily by the coefficient m_y of the aerodynamic yawing moment, the coefficient m_x of the aerodynamic rolling moment, and the coefficient c_z of the aerodynamic lateral force with consideration of the changes in the angle of slip β, the yaw angular velocity ω_y, and the roll angular velocity ω_x.

4. COEFFICIENTS OF TRANSVERSE AND DIRECTIONAL STATIC STABILITY AND THEIR INFLUENCE ON THE MOTION OF AN AIRPLANE WITH UNBALANCED THRUST. LATERAL AERODYNAMIC FORCE AS A FUNCTION OF SLIP

In performing calculations, investigating the lateral stability characteristics of aircraft, comparing various types of aircraft, etc., it is more convenient in practice to replace the derivatives of the forces and moments themselves by the derivatives of their coefficients:

$$c_z^\beta = \frac{\partial c_z}{\partial \beta}, \quad m_x^\beta = \frac{\partial m_x}{\partial \beta}, \quad m_y^\beta = \frac{\partial m_y}{\partial \beta}; \quad m_x^{\omega_x} = \frac{\partial m_x}{\partial \omega_x}; \quad m_y^{\omega_y} = \frac{\partial m_y}{\partial \omega_y};$$

$$m_x^{\omega_y} = \frac{\partial m_x}{\partial \omega_y}; \quad m_y^{\omega_x} = \frac{\partial m_y}{\partial \omega_x}.$$

These derivatives are usually known as the lateral stability coefficients. /34

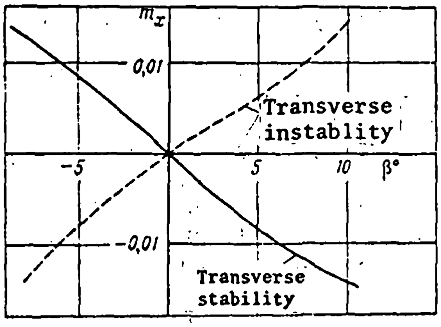

Figure 9. Coefficient m_x of Rolling Moment as a Function of Angle of Slip β.

It has been shown experimentally that in the range of small deviations, the quantities c_z, m_x, and m_y depend linearly on β, i.e., they vary in direct proportion to it. In exactly the same way, m_x and m_y are also linear functions of the angular velocities ω_x and ω_y. True, there are sometimes exceptions to this rule. For example, on certain airplanes, the vertical tailplane is partially blanketed by superstructures situated forward of them (blisters, turrets) in a certain, usually small range (±2°-5°) of angles of slip, and by the fuselage itself at larger angles of attack. The resulting decrease in flight path stability down to the point at which local instability appears ($m_y^\beta > 0$), which is similar to that indicated by the dashed curve in Fig. 4, may result in yaw oscillations that make aiming difficult and tend to increase crew fatigue.

From the standpoint of the size of the yaw overshoot on failure of a lateral engine, however, this kind of local instability should not be considered dangerous, since even at relatively small angles of slip the vertical tail comes out of the aerodynamic shadow and thereafter works normally.

The coefficients of transverse and flight path stability, m_x^β and m_y^β, have the strongest influence on the nature of the lateral motion (at least for aircraft of existing configurations).

The static transverse stability coefficient m_x^β is negative when slip of the aircraft is accompanied by the appearance of an aerodynamic rolling moment in the opposite direction, i.e., in the presence of static transverse stability (Fig. 9).

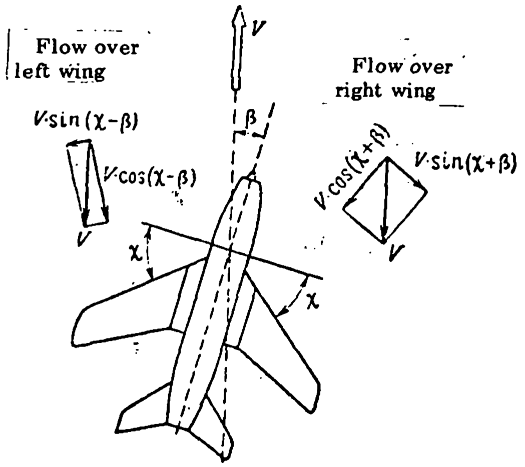

Figure 10. Influence of Wing Sweep on the Appearance of Aerodynamic Rolling Moments During Slip.

The appearance of a restoring (of direction such as to correct an existing slip) aerodynamic rolling moment is explained physically by the fact that the airplane's left and right wings are washed unequally by the oncoming airstream.

If the wing is straight and /35
has a certain dihedral, the angle of attack of the wing that has moved forward owing to slip is increased, and that of the wing that has dropped aft is reduced.

Superimposed on this phenomenon in the case of a swept wing is an effect in which the velocity of the oncoming airstream is decomposed into a chordwise (effective) component and a spanwise component. The former, which is numerically equal to V cos($\chi \pm \beta$), is the one that determines the lift from the corresponding side of the wing. This is what causes the additional rolling moment to appear when the airplane slips (Fig. 10).

Finally, the fuselage also has a certain influence on the rolling moment in slip. In a high-wing design, this is explained basically by the effect of the "armpit" between the fuselage and the root section of the wing, and in a low-wing design by blanketing of a certain part of the upper wing surface by the fuselage on the side opposite the slip, since, other conditions the same, transverse stability increases slightly for the high wing and decreases for the low wing (Fig. 11).

Thus, for an airplane with static transverse stability, the aerodynamic moment M_x tends to roll the airplane in the direction opposite to the direction of slip. The roll produces a lateral gravity component that pulls the airplane in the direction of the roll and thus helps return the velocity vector to the vehicle's plane of symmetry. Passing through this position on inertia, the airplane /36
acquires a slip in the opposite direction, the transverse stability moment begins to act in the opposite direction, and the entire sequence of events is repeated (with progressive damping if the airplane has dynamic lateral stability). Figure 12 schematizes the motion of a transversely stable airplane under the action of an external disturbance.

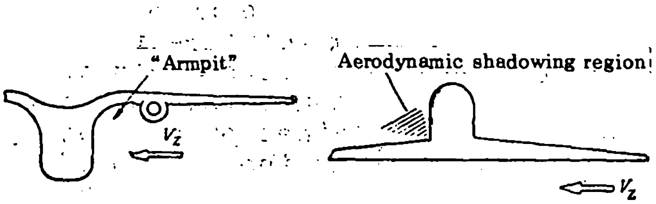

Figure 11. Rolling Moment During Slip on Aircraft with High and Low Wings.

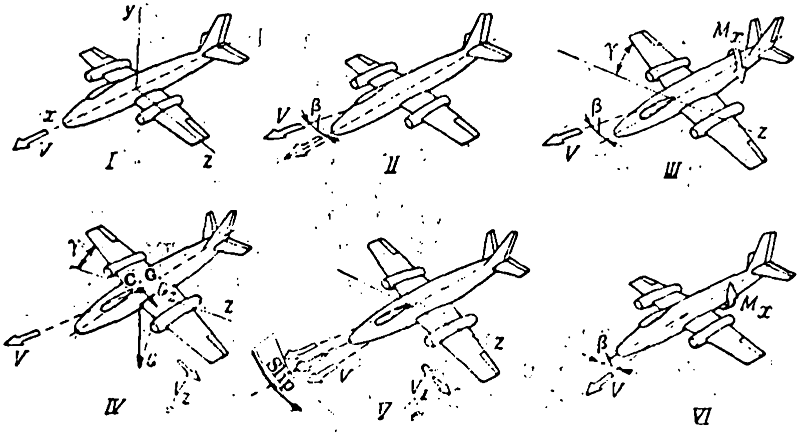

Figure 12. Oscillatory Divergent Motion of Airplane.

Let us assume that for some reason (for example, a lateral wind gust), an airplane that had been flying with zero roll and slip (I) has gone into slip at an angle β (II). The transverse stability moment (M_x) that arises as a result forces the airplane into a bank (III). In turn, the bank generates a lateral weight component (G_z) that pulls the airplane to the side, in the direction of the roll, i.e., to the left in our case (IV). A lateral velocity component (V_z), also directed to the left, appears.

As it increases, this component, which adds to the longitudinal component, first causes a return of the vector V to the airplane's plane of symmetry (i.e., it corrects the slip) and then deflects this vector in the opposite direction. /37

The airplane goes from slip against the roll to slip with the roll, in our case to the left (V).

As a result of the change in the slip direction, the transverse stability moment M_x also changes sign. The airplane comes out of the roll with angular velocity ω_x, passes through neutral, and rolls in the opposite direction (VI). Thereafter the oscillations damp out or build up depending on the sign of the dynamic oscillatory stability inherent to the particular aircraft.

Thus, the aerodynamic rolling moment that arises in this case also acts in the direction that corrects the slip, but in a more complex and indirect manner than the yawing moment. The motion occurs not in one plane, but in two: the yaw plane (xoz) in which the initial disturbance occurred and the roll plane (yoz), in which there was previously no disturbance. By far the greater number of the rolls that occur in flight in a bumpy atmosphere are not due directly to external disturbances, but are rolling reactions of a transversely stable airplane to slip. This reaction almost always involves the appearance of rolling motions of the airplane.

Sometimes the special literature refers to transverse stability as "the airplane's capacity for automatic elimination of any roll angle that develops."

This formulation cannot be recognized as altogether accurate, since it is inconsistent with the definition $m_x^\beta = \partial m_x/\partial\beta$ and is, as will be shown below, a possible source of certain widely held misconceptions.

It would be more accurate to say that static transverse stability is the tendency of the airplane to eliminate slip by rolling in the reverse direction. Sometimes, as in the case of straight-line slip, this tendency is actually aimed at bringing the airplane out of a bank. In general, however, the manifestation of transverse stability is not directly related to the presence of roll.

Thus, in a coordinated turn (a turn executed without slip), the presence of transverse stability by no means gives rise to an aerodynamic rolling moment.

However, as will be shown below, transverse static stability is manifested after an unbalanced engine failure in a manner directly opposite to what we should expect on the basis of the above formulation — an airplane that had been flying with zero roll has a tendency to roll, and sometimes a very strong one, after failure of a lateral engine. /38

It may seem strange at first glance that a property such as stability tends to aggravate the divergent motion of the airplane. In reality, however, there is no contradiction. Or, more accurately, the contradiction is purely one of terminology.

Observance of the necessary rigor of formulation in defining the notion of transverse stability is especially important because no other problem of the stability and controllability of aircraft gives rise to such frequent misunderstandings, and in no other case is there such a gap between the notions used in aerodynamics on the one hand and the notions developed by flight personnel on the other. Pilots are more likely to call an airplane transversely stable if it maintains a constant roll angle easily. Unfortunately, however, it is impossible to achieve this by purely aerodynamic means (without the use of special automatic systems): the aerodynamic rolling moment is not directly related to the roll angle. They are related only by slip. And while the relation between the rolling moment and slip is a rather stable quantity under a given set of conditions, one determined by the sign and absolute magnitude of the coefficient m_x^β, there is no consistent relation between slip and roll in the general case. Therefore, if we think of the airplane as being capable of conscious actions, like a living creature, its banking as an effect of transverse stability is not its purpose (elimination of the roll), but only a means to the attainment of another purpose – elimination of slip. Sometimes attainment of this goal requires a reduction of roll, and it is then reduced. Sometimes, however, as after an unbalanced engine failure, the reverse occurs: the roll increases sharply.

The terminological imprecision that has resulted in failure to distinguish transverse static stability clearly from the concept of good transverse stabilization of the airplane has led to misunderstandings on more than one occasion. Thus, all pilots who participated in the testing of one heavy four-engined airplane agreed unanimously that the transverse stability of the airplane required improvement. However, some of them took the view that its transverse stability should be increased, and others wanted it to be lowered. Correspondingly contradictory design recommendations were arrived at on the basis of these diagnoses: increasing the wing dihedral in one case and reducing it in the other.

In testing another airplane, the crews were unanimous in reporting good characteristics for the machine's behavior in the roll plane. It had no tendency to rock from side to side in bumpy /39 air, did not bank excessively sharply on simulated failure of one engine, and was easily put into and taken out of turns.

However, when the quantitative transverse stability characteristics of this airplane were measured in later tests and it was found that it had a near-zero coefficient m_x^β, i.e., the airplane was transversely neutral, the test report indicated the desirability of increasing its transverse stability.

In meeting this requirement, the designer increased the wing dihedral by 1°, with the result that the airplane lost some of the positive properties previously inherent to it.

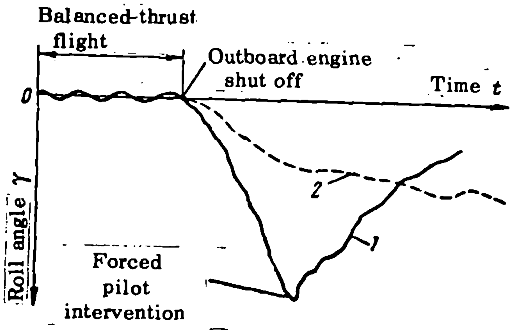

Figure 13. Response of Airplane to Unsynchronized Engine-Thrust Changes on Throttling Forward: 1) Before modifications; 2) after increase of negative dihedral and vertical-fin area.

It is also possible to point to contrary examples, in which proper understanding of the essentials of the phenomena attending manifestation of transverse stability and competent adjustment of the characteristics of this stability have made it possible to eliminate undesirable lateral-motion effects previously inherent to the particular type of airplane.

When its throttles were pushed forward at low altitude in a landing approach, one of the first copies of a new passenger airplane rolled so suddenly and severely that only quick and incisive pilot actions prevented its wing from striking the ground. The cause of this behavior was established quickly: it was found that the airplane had excess transverse stability, with the result that the angle of slip that appeared with the inevitable imperfect synchronism of engine-thrust buildup in response to the throttles produced a strong rolling moment. The appropriate modifications were introduced into the design of the aircraft: the area of the vertical tailplane was increased by a factor of nearly one-and-a-half and the wing dihedral was reduced by 1°. The consequences of this reworking became evident at once. The airplane's behavior improved substantially: as shown in Fig. 13, even total shutdown of an outboard engine failed to produce any sharp tendency to roll.

The above examples, the list of which could easily be increased, confirm that the steady stabilization of an airplane in roll angle is not identical to static transverse stability, which is characterized by the sign and absolute magnitude of the coefficient m_x^β.

The coefficient of static directional stability $m_y^\beta = \partial m_y / \partial \beta$ is also negative if the airplane is directionally stable, i.e., if the appearance of a slip angle is accompanied by the appearance of a yawing moment so directed as to align the airplane's pitching plane with its velocity vector, which is equivalent to correcting the slip. Since this motion of the airplane resembles the rotation of a weathercock, static directional stability is also often referred to as weathercock stability.

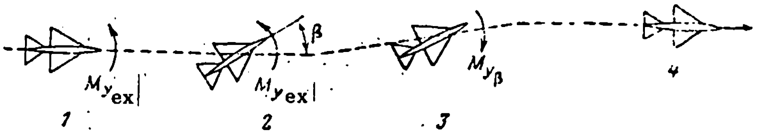

Figure 14. Effect of an Airplane's Directional Stability in Isolation: 1) An external yaw disturbance moment $M_{y.ex}$ is applied to the airplane; b) under the action of the moment $M_{y.ex}$, the airplane turns, and an angle of slip β appears; 3) in the presence of β, a restoring weathercock-stability moment $M_{y\beta}$ appears; 4) under the action of the moment $M_{y\beta}$, the airplane returns to its original heading.

The basic design element of an airplane that produces directional stability is its vertical tailplane – the fin, rudder, and "fences" on the tail section of the fuselage. The larger the static moment $S_{v.t}l_{v.t}$ of the vertical tailplane ($S_{v.t}$ is its area and $l_{v.t}$ is the distance from the airplane's center of gravity to the vertical-tailplane center of pressure), other conditions the same, the greater will be the directional stability. /40

It is important to note that the results of a disturbance are countered most naturally under the action of directional stability: the deflected airplane turns back around its vertical axis until its plane of symmetry is realigned with its velocity vector, i.e., until the slip vanishes. All of the motion takes place in only one plane – the same one in which the deflection from the original flight condition took place. No motions occur in the other planes (Fig. 14).

In practice, of course, such behavior of the airplane is possible only in extremely rare cases – with observance of the condition $\Sigma M_x = 0$, i.e., transverse neutrality and in the total absence of other transverse moments (due to unbalanced ventilation of the wings, the influence of ω_y on ω_x, etc.).

In the general case, however, the real lateral motion of an airplane is determined by the joint action of transverse and directional static-stability moments and certain other moments of which we shall speak below, and whose influence is, as a rule, less strongly manifested than that of m_x^β and m_y^β.

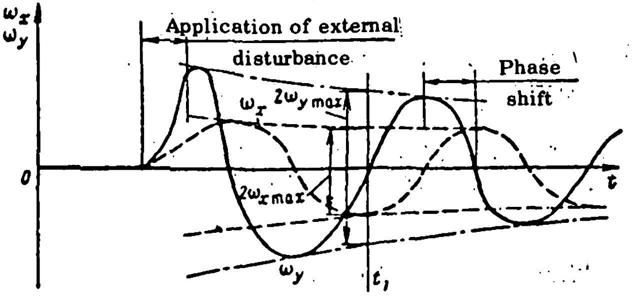

Figure 15. Lateral Oscillations of an Airplane (Illustrating the Phase Shift Between Changes in the Roll and Yaw Angular Velocities):

$$\varkappa = \frac{2\,\omega_{x\,max}}{2\,\omega_{y\,max}}$$

Accordingly, the divergent lateral motion of an airplane is, in the general case, also a rather complex combination of yawing and rolling motions.

The relation between /41
these two motions is evaluated quantitatively with the index

$$\varkappa = \frac{\omega_{x\,max}}{\omega_{y\,max}}.$$

The subscript "max" indicates that this calculation makes use of the maximum amplitude values of the angular rates of the transverse and directional divergent motions, taken from their envelopes, which, generally speaking, correspond to different points in time owing to the phase shift between the oscillations of ω_x and ω_y (Fig. 15).

Either roll or pitch may dominate in the lateral divergent motion of the airplane at different values of κ, i.e., with different relations between the degrees of transverse and directional static stability.* By adjusting these coefficients (by varying /42
the area of the vertical tailplane and the wing dihedral and by using various types of automatic devices), the designer can adjust the character of the lateral motion in the desired direction.

It therefore becomes necessary to establish what kind of motion is most desirable, or, in other words, which method of self-correction of slip – by roll or by yaw – is to be preferred?

Flight experience with many aircraft presenting a variety of lateral-stability characteristics provides grounds for giving the preference emphatically to yaw, in which, as we noted, slip is eliminated directly by motion in and only in the plane in which the disturbance arose. Eliminating slip by reverse banking, on

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*In addition to this ratio, the roll damping, defined by the coefficient $m_x^{\omega_x}$ and the relative compactness of the airplane

$$\mu = \frac{2m}{\varrho S l}$$

also have some influence on κ.

the other hand, reduces essentially to elimination of a divergence in one plane at the cost of creating a new divergence (not due to external disturbances) in another. In many cases, this secondary divergence may prove less desirable than the primary one, complicating the work of the crew and even presenting a greater hazard.

Such cases also include our present subject – the behavior of an airplane after failure of one engine situated outside its plane of symmetry.

It is known that when they fly through bumpy air, certain types of airplanes have a distinct tendency to rock back and forth from wing to wing. Even minor external disturbances cause them to bank strongly, requiring no little attention and expenditure of physical energy from the pilot. As we showed above, such behavior is usually due to excessive transverse static stability.

The roll angular velocities developed here and the roll angles themselves are usually so much larger than the yaw angular velocities and angles that the latter usually go unnoticed by the pilot. He senses the behavior of the airplane as transverse roll in pure form, although he is actually dealing with a combined lateral motion in both the roll and yaw planes. This circumstance further complicates pilot recognition of a lateral-engine failure on an airplane with excess transverse stability, since it may be difficult for him to identify the strong roll quickly and correctly as a consequence of a small yaw angle that is almost imperceptible against the background of strong rolling motion.

An excess of m_x^β over m_y^β results in oscillatory instability, and an excess of m_y^β over m_x^β in what is known as spiral instability. /43 However, flight practice has shown that these two effects are far from equally undesirable. Spiral instability, which occurs when the airplane goes into a smooth slow spiral with gradually increasing roll, has almost no effect on pilot handling, since this effect is easily countered by the pilot with no appreciable expenditure of effort or attention even if it is not stopped by the next external disturbance. It may reach dangerous proportions only in the improbable case in which an airplane is flown hands-off and left to itself for a considerable time, ranging into the tens of seconds. Many modern aircraft have moderate spiral instability, and it is characteristic that their pilots do not even suspect it and remain unconvinced after performing special tests involving observation of the airplane's motion without pilot intervention for considerable times after application of an external disturbance.

Counteracting oscillatory instability, on the other hand, requires practically continuous work from the pilot. It is impossible to ignore this form of instability – no special experiments are necessary to bring it out, since any lateral external

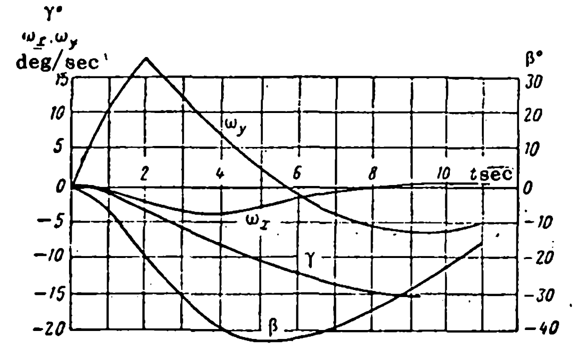

Figure 16. Divergent Lateral Motion of Aircraft: m_x^β = = -0.0002; m_y^β = -0.0008; κ = = 1.10.

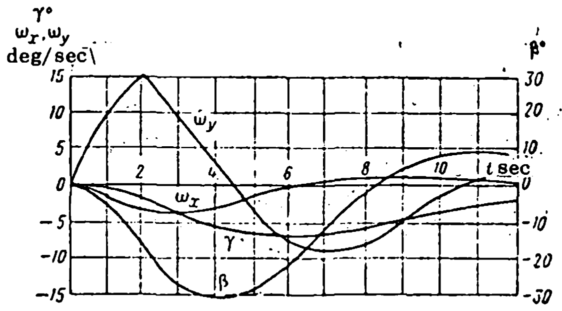

Figure 17. Divergent Lateral Motion of Aircraft: m_x^β = = -0.0002; m_y^β = 0.0024; κ = = 0.31.

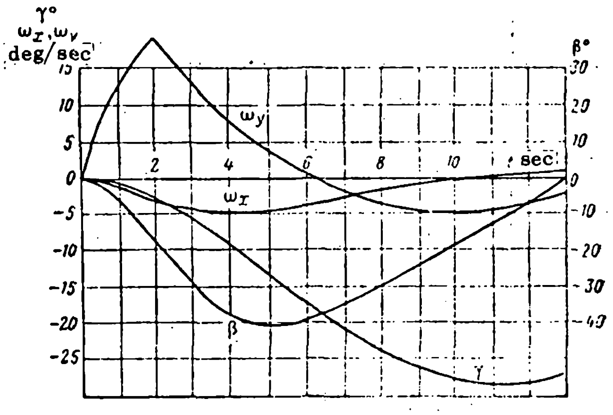

Figure 18. Divergent Lateral Motion of Aircraft: m_x^β = = -0.0006; m_y^β = -0.0008; κ = = 3.34.

disturbance causes an airplane with oscillatory instability to roll sharply. Thus, on sudden failure of an engine, certain aircraft with excess transverse stability, e.g., the Pe-2 dive bomber that was widely used during the war, would bank so strongly toward the out engine that the airplane would flip over if the pilot's responses were a little slow or imprecise.

This is clearly confirmed by curves (Figs. 16-20) that characterize the divergent lateral motion of a transonic jet aircraft with various values of the lateral static stability coefficients m_x^β and m_y^β. These curves were obtained by analog-computer calculations during which it was possible to vary these coefficients without changing the other parameters of the airplane — something that is difficult to achieve in the performance of prototype flight tests.

Table 2 lists values of the characteristics used for the lateral static stability coefficients in the five variations studied.

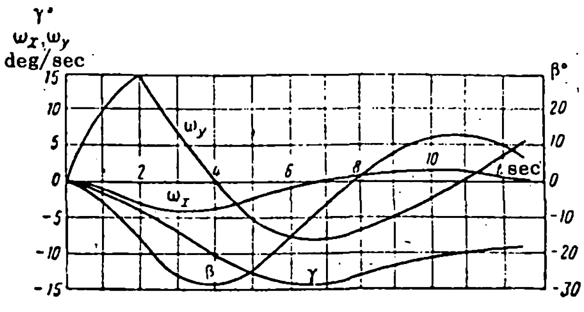

Figure 19. Divergent Lateral Motion of Aircraft: $m_x^\beta = -0.0006$; $m_y^\beta = -0.0024$; $\kappa = 0.97$.

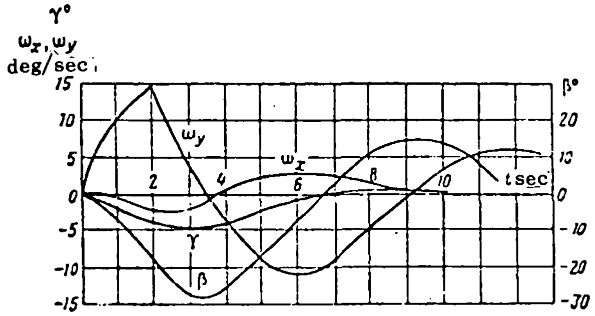

Figure 20. Divergent Lateral Motion of Aircraft: $m_x^\beta = 0$; $m_y^\beta = 0.0024$; $\kappa = 0$.

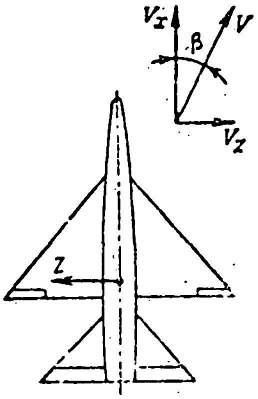

Figure 21. Development of Transverse Aerodynamic Force Z in Slip.

TABLE 2*

Variant No.	m_x^β	m_y^β	m_x^β / m_y^β	$\varkappa$
I	–0,0002	–0,0008	0,25	1,10
II	–0,0002	–0,0024	0,08	0,31
III	–0,0006	–0,0008	0,75	3,34
IV	–0,0006	–0,0024	0,25	0,97
V	0	–0,0024	0	0

*Translator's Note: commas represent decimal points.

All other characteristics – the coefficients $m_x^{\omega_x}$, $m_y^{\omega_y}$, $m_x^{\omega_y}$, $m_y^{\omega_x}$, and c_z^β, the data of the airplane G, S, l, J_x, and J_y, and its flight speed and altitude V and H – were assumed to be the same in all five of these variations.

Application of a yawing moment corresponding to failure of one of two wing-mounted engines in cruising operation ($P = 0.5P_{nom}$) was taken as the external disturbance. It was assumed that this unbalanced-thrust moment acted for 2 sec, after which it vanished and the subsequent motion of the airplane was free, i.e., as before, without intervention of the pilot and with the tail control surfaces and ailerons in the same neutral position. This scheme, while somewhat artificial, is convenient for investigation of the influence of static lateral stability characteristics. /44

Indeed, the influence of the coefficients m_x^β and m_y^β is fully evident from comparison of the curves (see Figs. 16-20).

Simultaneously, analysis of the curves clearly demonstrates the inconsistency of the commonly encountered notion according to which the nature of the airplane's divergent lateral motion is fully determined solely by the ratio of the lateral-stability coefficients, irrespective of their absolute values. Thus, the curves in Figs. 16 and 19 correspond to the same ratio $m_x^\beta:m_y^\beta$, but /45 the amount of slip developed at small absolute values of the two coefficients (chiefly the coefficients m_y^β) is one-and-a-half times greater than when they have large values. An obvious difference is also observed in the rolling motion: although the roll angle that appears is practically the same in both of these cases, the rates of the unfolding process (the time variation of the angular velocity ω_x) are widely different.

Thus, the divergent lateral motion of the airplane, and, in particular, its behavior on an unbalanced thrust failure, depend not only on the ratio of the transverse and directional static stability characteristics, but also on the absolute values of these characteristics. /46

In slip, a transverse aerodynamic force Z directed perpendicular to the plane of symmetry arises as a result of the unbalanced airflow past the parts of the airplane — fuselage, engine nacelles, and vertical tailplane (Fig. 21).

Experiments have shown that the coefficient of this force

$$c_z = \frac{2Z}{\rho S V^2}$$

varies approximately linearly with the angle of slip β. For this reason, the variations of the force Z with angle of slip are usually expressed in terms of the coefficient

$$c_z^\beta = \frac{\partial c_z}{\partial \beta}.$$

As will be shown below, the transverse force has a strong influence on the peak angle of slip of the airplane after failure of a lateral engine, and also on the characteristics of steady flight with unbalanced thrust. /47

5. ROLL AND YAW DAMPING. INFLUENCE OF ROLL ANGULAR VELOCITY ON YAWING MOMENT AND OF YAW ANGULAR VELOCITY ON ROLLING MOMENT (CROSS-ROTARY DERIVATIVES)

In the preceding section, we demonstrated the influence of slip on the appearance of the moments M_x and M_y and the influence of the force Z on the subsequent variation of these moments.

In addition to slip, however, the rolling and yawing moments are influenced by the roll (ω_x) and yaw (ω_y) angular velocities. Strictly speaking, they also affect the aerodynamic force Z, but to a much lesser degree than the slip; in analyzing the divergent lateral motion of the airplane, therefore, the effects of ω_x and ω_y on the force Z are usually neglected.

Roll damping is probably the most significant of the above effects of the angular velocities on the airplane's lateral motion following an unbalanced thrust failure.

In the presence of an angular velocity ω_x, the true angles of attack of the left and right wings are unequal as a result of geometrical addition of the translational velocity V and the circumferential velocity of each given cross section $\omega_x z$ (z is the distance between the given cross section and the airplane's plane of symmetry) (Fig. 22). The local angles of attack in the cross sections of the dropped wing are found to be larger than those in the cross sections of the lifted wing.* Accordingly, the lift of the dropped wing will also be larger, with the result that a damping rolling moment appears.

The damping moment is always directed against the rotation. Hence, unlike other aerodynamic moments, it cannot be a restoring moment acting in the direction that eliminates an existing deflection. Herein lies the fundamental difference between damping and stability. /48 Nevertheless, in the overwhelming majority of cases, including that of lateral-engine failure, the influence of damping on the handling properties of an airplane is unquestionably favorable, since it resists the actual deviation from the initial flight regime, thereby softening the divergent motion of the airplane. Figure 23 shows the characteristics of the lateral divergent motion of the airplane to which the curves in Fig. 19 pertain, with

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*The dropped wing is the wing moving in the direction of its lower surface, and the lifted wing is the one moving in the direction of its upper surface, i.e., the motion is analyzed in a coordinate system bound to the aircraft. In this way, the situation does not change if, rolling about its longitudinal axis, the airplane turns wheels-up and the wing being lifted relative to the ground becomes the dropped wing and vice versa.

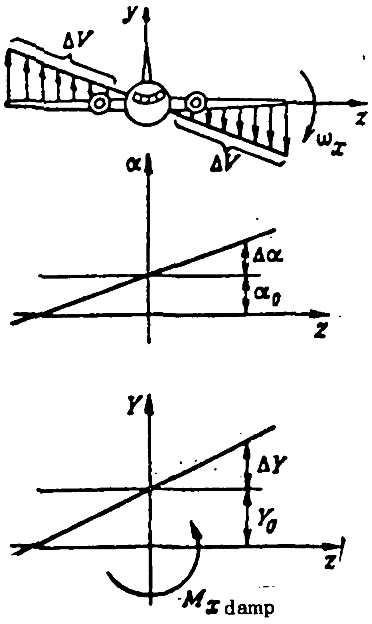


Figure 22. Illustrating the Roll-Damping Phenomenon. ΔV are the local circumferential velocities formed as the airplane rotates about its longitudinal axis (rolls); ω_x is the roll angular velocity; α is the angle of attack; α_0 is the angle of attack in unbanked flight; $\Delta\alpha$ is the local increment of the angle of attack on banking; Y is the lift in unbanked flight; ΔY is the local lift increment on banking; $M_{x\ damp}$ is the roll damping moment.

the difference that the degree of roll damping, which was the same in all five of the variants examined above, is reduced by half here. As a result, other conditions, the same, the roll angular velocity was found to be higher during the first 4-5 sec than in any of the other variants investigated, and the roll angle exceeded those in the other variants in the time segment from 2 to 7-8 sec, i.e., actually throughout the entire period beyond which it would hardly be possible to consider the motion of the airplane after engine failure to be taking place without pilot intervention.

Since the damping phenomenon is due to force interactions between parts of the airplane and the air, it depends on air density. At high altitudes, where the air is thin, natural damping is therefore much less strongly manifested than at medium altitudes, not to mention low altitudes.

In speaking of damping, we should not overlook the fact that in analyzing its physical nature, we have assumed the existence of a direct functional relationship between the increment of the angle of attack and the increment of lift. However, we know that in the range of supercritical angles of attack, this relationship is inverted: lift decreases with increasing α and autorotation begins in response to a minute external impulse. Thus, autorotation can be regarded as a phenomenon that is essentially the opposite of damping.

Converting from the moments to /49 their coefficients in much the same way as was done above in investigating the influence of slip on the moments M_x and M_y, we obtain the rotary derivative characterizing roll damping:

$$m_x^{\omega_x}=\frac{\partial m_x}{\partial \omega_x}.$$

The sign of this derivative is always negative, since the damping moment is by its very nature opposed in direction to the angular velocity in all possible flight cases, with a sole exception – that of the autorotation mentioned above.

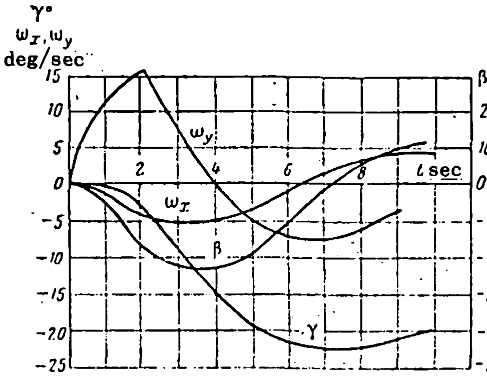


Figure 23. Divergent Lateral Motion of Airplane with Reduced Roll Damping.

Thus, it follows from Fig. 22 that in the presence of an angular velocity ω_x, the local values of the angles of attack α change on cross-sections of both wings. However, this also implies that the aerodynamic drags of the wings will also differ: that for the dropped wing will be greater than that for the lifted wing. Consequently, rotation of the airplane on its longitudinal axis results in the appearance of an aerodynamic moment about the vertical axis as well. The airplane tends to turn in the direction of the dropped wing. We note, incidentally, that the existence of this relation helps maintain coordination on entering and coming out of turns.

The dependence of the yawing moment on the roll angular velocity is characterized quantitatively by

$$m_y^{\omega_x} = \frac{\partial m_y}{\partial \omega_x},$$

which is sometimes known as the cross-rotary derivative of yaw with respect to roll.

Let us examine in similar fashion the yawing motion at angular velocity ω_y shown schematically in Fig. 24. We see from the figure that the right and left wings have unequal translational velocities and, accordingly, different aerodynamic drags and lifts. Consequently, the airplane's angular velocity ω_y also results in the appearance of secondary rolling and yawing moments. The lateral force $Z_{v.t}$ of the vertical tailplane that arises in the presence of the angular velocity ω_y owing to the "skidding" that is inevitable in this case also has a definite part in the generation of the yawing moment. /50

Quantitatively, the relation of the rolling and yawing moments to the angular velocity ω_y is characterized by

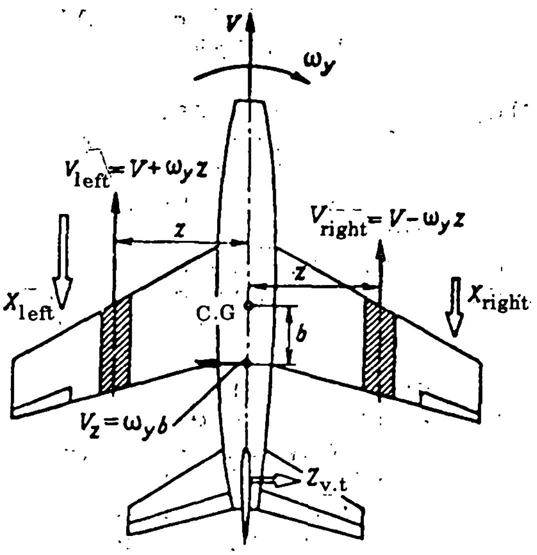


Figure 24. Generation of Yaw Damping Moment.

$m_x^{\omega_y} = \frac{dm_x}{d\omega_y}$ — the cross-rotary derivative of roll with respect to yaw;

$m_y^{\omega_y} = \frac{dm_y}{d\omega_y}$ — the yaw damping.

Of the above four rotary derivatives, the roll damping $m_x^{\omega_x}$ which resists banking – the greatest hazard in this case – has the strongest and, at the same time, the most helpful influence on the airplane's motion after failure of a lateral engine. The yaw damping $m_y^{\omega_y}$ also exerts a helpful influence, but, as a /51 rule, a considerably weaker one; to some degree, it resists "skidding," i.e., yawing of the airplane into the range of large angles of slip. The cross-rotary derivatives $m_x^{\omega_y}$ and $m_y^{\omega_x}$ have a much less pronounced influence on airplanes of modern configurations. However, it must be noted that, unlike damping, the cross-rotary couplings are detrimental in cases of lateral-engine failure in that they tend to aggravate the divergence.

All of the basic quantities that appear in the equations of the airplane's lateral divergent motion can be determined with accuracy sufficient for practical purposes from model wind-tunnel tests or from approximate empirical formulas. Consequently, the characteristics of this motion under the action of an unbalanced-thrust moment (or some other known external disturbance) can also be determined by integrating this equation system on an electronic computer or by some other method.

Thus, the investigator and designer have an opportunity to predict the behavior of the airplane after failure of a lateral engine and, if necessary, to specify means of improving this behavior: increasing vertical-tailplane area, reducing wing dihedral, or using artificial means of stabilizing the airplane with respect to the appropriate axes (automatic oscillation dampers, etc.).

6. PECULIARITIES IN THE BEHAVIOR OF TURBOPROP-ENGINED AIRCRAFT ON FAILURE OF A LATERAL ENGINE. THE PHENOMENON OF REVERSE THRUST

On propellerless airplanes, the yawing moment developed by the drag of the failed engine is usually small by comparison with the thrust of its counterpart on the other side, which in this case develops most of the total unbalanced-thrust moment. At the same time, the lateral engines of most turbojet aircraft are also mounted on shorter arms off the plane of symmetry than those of propeller aircraft, in which engine placement is determined in large part by propeller diameter.

The aerodynamic-drag moment of a turboprop engine is particularly large because its relatively great distance from the airplane's plane of symmetry combines with the extremely large aerodynamic drag of the windmilling propeller. In certain flight situations (in the low-speed range), certain types of turboprop engines have drags one-and-a-half to two times larger than the thrust of the same engine at rated power.

The principal cause of this drag consists in the fact that rotation of a nonrunning turboprop engine ("cold cranking") requires application of a considerably larger torque than turning a nonrunning piston engine. /52

The energy used to compress the mixture (or the air if the fuel valve to the failed engine is closed) in the cylinders of a piston engine is not completely lost, but does some useful work during the subsequent expansion cycle. The external torque has only to overcome friction between the parts of the engine being turned and to compensate heat losses from the compressed mixture to the cylinder walls.

Cold cranking of gas-turbine (including turboprop) engines, in which the energy used to compress the air in the compressor subsequently does almost no useful work toward turning the engine, is another matter. In this case, therefore, cold cranking requires application of a torque sufficient not only to overcome friction in the engine, but also to do all of the air-compression work in its compressor.

In the case of a turbojet engine (TJE), this results in a corresponding drop in the autorotation rpm with no noticeable drag increase. On a turboprop engine (TPE), however, the propeller-speed governor reduces the pitch of the propeller blades so as to maintain rpm at the level set on the governor even under windmilling conditions. Working as a windmill, the propeller develops the necessary torque, which is sometimes very large, but at the same time it inevitably develops an extremely high drag, which is sometimes referred to as reverse thrust.

To obtain a rough estimate of this drag, it can be assumed that each thousand horsepower of the TPE's output produces about 900-1000 kg of reverse thrust when the engine fails and its propeller windmills.

If we compare the power developed by a turboprop engine at the turbine with the useful power available at the propeller, the former is found to be 2.5 to 3 times larger than the latter. The difference between these two figures is expended in overcoming the friction between the moving parts of the engine and turning accessories mounted on it, but primarily in turning its powerful compressor.

In addition to the above circumstances, it must also be remembered that modern turboprop engines have nominal power outputs two or three times greater than those of the latest piston engines or greater, and that this increase in nominal power, irrespective of the fundamental characteristics of the TPE that were set forth above, is in itself sufficient to increase further the torque necessary to turn it over.

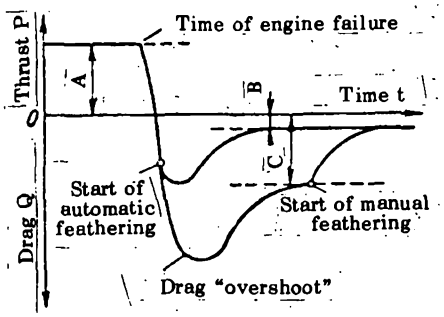
Under real flight conditions, the power required to autorotate a failed engine can be obtained only from the rotation of the propeller in the oncoming air stream, i.e., in the final analysis at the expense of the thrust of the engines that remain in operation. /53

Turboprop engines of the compound type, such as the TVD-10, have appeared in recent years; in these engines, the propeller and compressor are not rigidly kinematically coupled. The propeller of such an engine can windmill with the compressor stationary (or turning at negligible speed), so that it does not develop strong reverse thrust.

Quick and sure detection of a failed engine is sometimes even more difficult on turboprop aircraft than it is on aircraft with piston engines. By switching automatically to smaller setting angles, the propeller governor maintains a previous rpm setting in a broad range of speeds even after engine failure. It is therefore difficult to identify a failed engine by reading the revolution counters. In such cases, the variations of the after-turbine gas temperature or the fuel pressure, which will be somewhat different for a failed engine than for the running engines, can be used as indications in such cases. However, the clearest indications are obtained from the torquemeter (TM). It is this instrument that should be regarded as basic for the identification of a failed engine in flight on a turboprop airplane.

Needless to say, it makes no difference from the standpoint of programming the first actions of the pilot precisely which engine has failed. In this case, the pilot responds as quickly as possible without awaiting identification of the specific

"culprit" behind the divergent motion, which requires immediate countering and, for the most part, makes it painfully clear by itself on which side the failed engine is located. However, subsequent actions (e.g., positive feathering of the propeller on the failed engine, closing fuel valves, etc.) requires exact knowledge not only of the side on which the engine has failed but precisely which engine it is. This has made it necessary to equip turboprop aircraft with special engine-failure-indicating systems (to indicate a total loss or decrease of thrust). However, practice has shown that not even this is enough. In certain flight conditions, the drag of a windmilling turboprop-engine propeller becomes so large that each additional second for which this drag acts aggravates the deviation of the airplane from its initial condition appreciably. Only automatic feathering of the propellers of failed engines can ensure performance of this vitally important operation both quickly enough and in freedom from error. For this reason, a full-time (in operation in all flight conditions and at all en- /54
gine settings) automatic feathering system should be a mandatory accessory to the powerplant of any turboprop airplane.



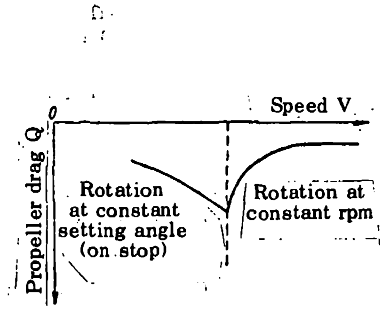


Figure 25. Variation of Aerodynamic Drag ("Reverse Thrust") of Turbojet Engine Propeller with Manual and Automatic Feathering. A) Torque of running engine; B) drag of failed engine with feathered propeller; C) drag of failed engine with windmilling propeller.

Figure 26. Aerodynamic Drag of Windmilling Turbojet-Engine Propeller as a Function of True Flight Speed.

This system goes into operation automatically and feathers the propeller in response to tripping of various types of sensors that respond, for example, to a drop in torque, to the appearance of a definite predetermined amount of propeller drag ("reverse thrust"), to overspeeding (racing), to a drop in oil pressure, etc. This ensures operation of the automatic feathering system in practically all possible cases of engine failure, but it still does not relieve the pilot of the need to counter the divergent motion of the airplane competently and in time. Even automatic feathering of the propeller on the out engine requires a certain amount of time — 4 to 8 seconds — during which the drag of the propeller may build up an appreciable decelerating inpulse and strongly influence the behavior of the airplane (Fig. 25).

Finally, it must be noted that the propeller drag of an autorotating turboprop engine is different at different speeds: it has a maximum when the blades are set against their stops, which occurs at an indicated speed on the order of 270-320 km/h for most modern aircraft. At lower speeds, propeller drag decreases to some extent. It drops even more rapidly on entry into the range of higher, cruising flight speeds* (Fig. 26).

In addition to the above circumstances that influence the magnitude of the unbalanced-thrust moment, piston- and turboprop-engined aircraft (especially the latter) are subject to yet another factor, one that tends to make the airplane roll over even more sharply in the direction of the failed engine — the unsymmetrical distribution of lift along the wingspan that results when the wash from one of the propellers is removed. The stream of air thrown backward by the propeller and over the segment of wing behind it increases appreciably the local flow velocity over the wing and, consequently, the lift developed by the particular segment of the wing. The lift increment due to propeller wash may be quite substantial: thus, for example, if we compare a modern turboprop aircraft flying with the engines at idle with one flying at rated power, then, all other conditions the same (equal angles of attack, Mach numbers, etc.), the lift coefficient may be 30-40% larger in the latter case than in the former. In cruising situations, of course, the effect of propwash on the wing is weaker than it is at full rated power, but it remains substantial. /55

Failure of one of the engines and disappearance of the wash over the corresponding wing segment therefore give rise to imbalance in the spanwise distribution of lift and a rolling moment directed, like the lateral-stability moment, in the direction of the failed engine.

It is difficult to predict which of these moments will be larger in magnitude. This depends both on the flight regime and, in particular, on the type of airplane. There is no secondary wing wash in the case of turbojet-engined aircraft and, consequently, the rolling moment that appears on engine failure owes its origin basically to slip and the emergence of transverse stability. On the other hand, we might conceive of a turboprop airplane with a straight wing having a dihedral angle such that the absolute value of the transverse-stability coefficient m_x^β equals zero. On failure of a lateral engine on such an airplane, the appearance of slip will not cause a tendency to roll, but the propwash imbalance will have its full effect.

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*See, for example, [13].

7. PECULIARITIES OF THE BEHAVIOR OF A SWEPT-WING AIRCRAFT AFTER FAILURE OF A LATERAL ENGINE. PHENOMENON OF REVERSED ROLLING REACTION TO SLIP

As we showed above, the nature of an airplane's divergent motion after failure of a lateral engine is determined to a major degree by the ratio of the roll and yaw angular velocities. It is desirable that there be no tendency to bank sharply in the direction of the failed engine. /56 The most effective means of preventing this dangerous tendency is proper selection of the degree of transverse static stability, which depends on a number of factors, but primarily on the wing dihedral angle.

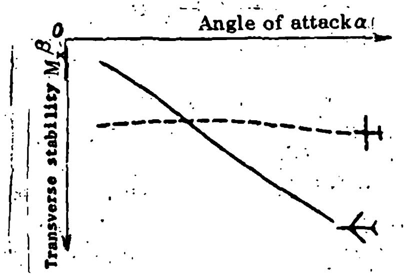

Figure 27. Coefficient of Transverse Static Stability m_x^β as a Function of Angle of Attack α. The solid line represents the swept wing and the dashed line the straight wing.

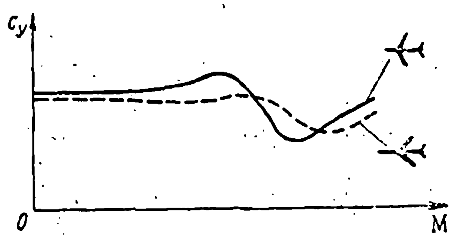

Figure 28. Lift Coefficient c_y as a Function of Mach Number. Solid line: wing with small sweep angle; dashed line: wing with large sweep angle.

It might seem that the designer has in his hands a way of providing each airplane with the transverse-stability characteristics most favorable in all possible flight situations, including unbalanced engine failure.

Unfortunately, not all aircraft design configurations admit of such easy attainment of the desired transverse static stability. For one thing, serious difficulties are encountered with swept-wing aircraft, whose transverse stability depends strongly on angle of attack (Fig. 27). With increasing angle of attack (in the landing approach, in flight near the practical ceiling, during a turn with the maximum permissible bank and the corresponding g-force), the transverse stability of the swept wing increases sharply, so that failure of a lateral engine becomes especially dangerous in such flight situations.

It is necessary to accept the fact that by selecting a dihedral angle that ensures the desired transverse-stability characteristics at some one (usually the cruising) angle of attack, the designer leaves the transverse stability either higher or lower than optimum at all other angles of attack.

For this reason, almost all swept-wing aircraft without automatic stabilization devices (or when such devices are not in operation) have inherent excess transverse stability in flight at large angles of attack, and hence also unpleasant handling characteristics, such as side-to-side rocking in a bumpy atmosphere and a sharp banking tendency on unbalanced engine failure. This was one of the factors that gave rise to the use of various types of "automatic stabilizers" (oscillation dampers), usually electronic, on modern aircraft — devices that practically eliminate or, in any event, greatly mitigate the manifestation of these unfavorable handling characteristics.

Apart from the angle of attack, the transverse stability of a swept wing is sometimes influenced by Mach number (the ratio of /57 flight speed to the speed of sound).

Here we refer to what is known as a reversed rolling reaction to slip, which is one of the possible manifestations of shock stall.

The usual rolling reaction of an airplane to slip is inherent to a transversely stable machine and, as was shown above, is manifested in a tendency to bank in the direction opposite to that of the slip. Thus, the normal airplane will roll in the direction of the deflected rudder pedal, and, in the event of failure of a lateral engine, in the direction of that engine. The pilot has been accustomed to this behavior throughout his entire flying life, and is fully justified in regarding it as "direct" or normal.

However, it is found that in a certain range of Mach numbers around unity, this familiar rule is violated and, still worse, reversed.

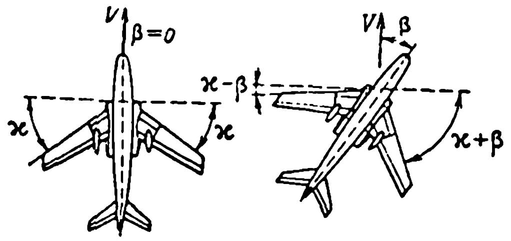

Figure 29. Change in Effective Sweep Angles χ of Left and Right Wings in Flight with a Slip β.

Figure 28 illustrates the change that takes place in the lift coefficient as a function of Mach number with various wing sweep angles. At subcritical Mach numbers, lift depends little on sweep. The existing insignificant difference tends to favor small sweep angles, at which the lift obtained is slightly higher than it is at large ones. However, after the critical Mach number has been reached, the lift coefficient drops sharply, and then recovers to near-subcritical values. What is important here is that this "trough" on the lift-coefficient curve begins later (at larger M) with larger sweep angles and is less distinct than for small ones. As a result, the curves in Fig. 28 intersect in such a way that, in contrast to the usual situation, there is a certain range of Mach numbers in which lift increases with increasing wing sweep angle and decreases as it decreases.

Figure 29 shows a swept wing in plan view during slipping flight. It is as though the wing had a smaller sweep angle on the side toward which the slip has occurred, and a larger one on the opposite side as compared to symmetrical flight. As a result, the lift is also found to be higher on the side opposite the slip in this range of Mach numbers. The rolling moment that arises as /58 a result will act in the direction of the slip.

If a rudder pedal is deflected in flight in the Mach-number range in which this phenomenon is observed, the airplane will roll in the direction opposite to this deflection.

This behavior of the airplane, which is essentially transverse static instability ($m_x^\beta > 0$) is known as reversed rolling reaction to slip. It can manifest only in the Mach-number range in which the relation indicated in Fig. 28 exists between the "troughs" of the lift curves for the different sweep angles.

Practical flying has shown that, although the presence of reversed rolling reaction to slip requires increased attention on the part of the pilot in certain flight situations, the seriousness of the phenomenon should not be overestimated.

Very little use is made of the rudder in flying modern aircraft. The lateral motion of the airplane (turns, spirals, and other maneuvers) is controlled practically exclusively with the ailerons. Probably the only exceptions to this rule are takeoff and landing, when wind gusts (especially from the side) must sometimes be countered with appreciable deflections of the rudder. At takeoff and landing, however, the Mach number is so far below critical that none of the manifestations of shock stall, including reversed rolling reaction to slip, can occur in these situations. In most other cases, however, the rudder deflections are very small and, consequently, the slip angles that result from them are just as small.

It is this circumstance that apparently explains why pilots often fly at speeds at which the reversed rolling reaction to slip occurs without noticing this effect. It is characteristic, for example, that the reversed reaction has been observed in tests of many aircraft only during special procedures ("kicking" the rudder at various Mach numbers or in slipping acceleration), while it has gone unnoticed in flights of other profiles, during which the airplane ran through the entire Mach-number range repeatedly. /59

In ordinary piloting, therefore, the pilot will very probably experience no handling trouble due to the reversed reaction.

However, there are exceptional flight regimes in which the pilot uses more or less substantial rudder deflections even at high speeds. And here the unexpected manner in which the reversed reaction appears (which is due to the very fact that the pilot has usually never observed this effect and has not become used to it) may have highly unpleasant consequences.

These exceptions include flight in tight formation (for example, when a pilot adjusts his position in interval relative to the leader), pulling a high-speed airplane out of a steep spiral, and — failure of a lateral engine.

If this failure takes place in the Mach-number range in which the reversed rolling reaction to slip is manifested, the airplane will bank not in the direction of the out engine, but in the direction of the good one.

It is true that in most cases the degree of transverse instability encountered in the reversed rolling reaction of an airplane to slip is small, and the banking of the airplane, though in the "unexpected" direction, is quite sluggish and is countered without difficulty by the pilot.

At the Mach number corresponding to the boundary between the ranges of the normal and reversed rolling reactions to slip, the airplane's transverse stability is essentially zero and failure of one of the engines will cause only a yaw without the corresponding roll, something that can be rated only favorably from the pilot's viewpoint.

Outside of the reversed-reaction region, failure of a lateral engine on an airplane with a swept wing at comparatively low airspeeds, i.e., at large angles of attack, results, as we have noted, in a stronger tendency to bank than it does at high airspeeds and correspondingly small angles of attack.

8. OPTIMUM PILOTING PROCEDURES ON UNEXPECTED LATERAL-ENGINE FAILURE

The motion of an airplane one of whose lateral engines has unexpectedly failed is, as we showed above, qualitatively determined by the combination of a number of its inherent design and aerodynamic parametrrs. These include the positions of the engines, their type (TJE, TPE, etc.), their operating setting at the instant of failure, the distribution of the airplane's mass along its longitudinal axis, its directional and transverse static stability characteristics, and aerodynamic damping (especially roll damping) and other factors. Differences in the above parameters result in corresponding idiosyncrasies of the aircraft on unbalanced thrust failure. /60

However, the behavior of the airplane in this complex situation is not determined by design and aerodynamic characteristics alone.

Great importance attaches to the actions of the pilot: their speed, incisiveness, and proportioning. Pilot actions explain the well-known fact that the same airplane being flown in the same flight regime under the control of one pilot will not leave the acceptable range of spatial attitudes after failure of a lateral engine, while if another pilot is at the controls it will go to dangerous roll and slip angles. It goes without saying that piloting should not require excessively high skill of the pilot or stand in contradiction to the conventional and customary procedures for handling an airplane in any of the cases possible in flight, including sudden engine failure. Such are the requirements of most of the standards currently in effect for the airworthiness of aircraft. However, a pilot reaction to engine failure that takes the correct direction, is of proportionate magnitude, and does not take longer than the allowed delay time should not be made a criterion of extremely high skill on his part – if, of course, the characteristics of the vehicle, and primarily its power-weight ratio, stability, and controllability support performance of the necessary maneuvers and conform to the above standards.

To ensure timeliness of the pilot's reaction to the appearance of an unbalanced-thrust situation, it is necessary that his actions to counter the deviations from the original flight regime follow directly from the incipient divergent motion, irrespective of his conscious analysis of all of the facts of the event, i.e., establishing that a failure has occurred, determining which of the engines has failed, not to mention taking any possible measures to restore the powerplant to normal operation.

It goes without saying that all of these actions, which are often made difficult by the properties of the devices used to indicate the performance of modern powerplants, must be undertaken, but independently of, and only after, all necessary measures to correct the divergent motion of the airplane, since any delay of the latter may have dangerous consequences.

The results of many psychophysiological experiments, which have been confirmed in aviation practice (and in the practical activity of people operating complicated dynamic systems of other types), indicate that the most dependable way to ensure sufficiently rapid and, at the same time, incisive actions is to train the /61 individual in performance of these actions – to establish automatism and make the necessary reaction habitual.

On the other hand, it is obvious that only a reaction that is repeated many times can become a habitual, thoroughly conditioned reaction. The individual does not become habituated to infrequent occurrences, which, in our day, include aviation-engine failures.

Hence follows the expediency of systematic training of the flight crew to control the aircraft as lateral-engine failures are simulated. In the interest of ensuring the necessary safety in such training, it is necessary to elaborate the procedure on the principle of progressive complication. The procedure should begin with smooth throttling back, by the trainee pilot himself, of the rpm (thrust) of an engine located closest to the airplane's plane of symmetry at near-cruising speed, and should progress gradually to the stage at which the instructor or inspector abruptly shuts down a critical (i.e., as a rule, outboard) engine during a climb at relatively low translational speed with the powerplant running at high (nominal or maximum) output.

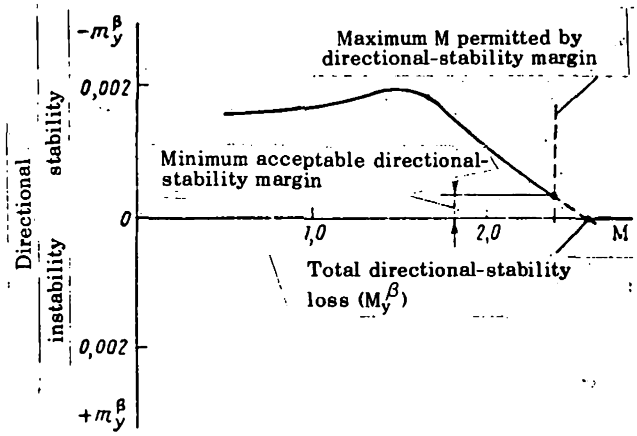

Figure 30. Coefficient of Static Directional Stability m_y^β of a Supersonic Aircraft as a Function of Mach Number.

In addition, and independently of these training flights, it is important that the pilot hold himself in internal readiness to respond quickly and correctly to an unexpected engine failure at all stages in the flight – from the takeoff run to the landing roll. He must be aware of the fact that the sharpness of the airplane's divergent motion may differ greatly between the various flight regimes. Thus, at high altitude, where the lower density of the air causes a sharp decrease in damping, an airplane in flight in the range of subcritical attack angles will go into its roll, other conditions the same, much more sharply than it will at low altitude. In the same way, there is reason to expect different rates of the divergent motion on failure of a lateral engine of the same airplane at different flight speeds. We pointed out above that the aerodynamic drag of a windmilling turboprop engine has a distinct maximum at a certain speed; naturally, in the event of engine failure at this speed, the increased unbalanced-thrust moment will produce an effect correspondingly stronger than that experienced at other initial speeds. Another range of flight speeds in which lateral-engine failure is especially dangerous corresponds to the maximum permissible Mach numbers of supersonic aircraft (Fig. 30).

A clear conception as to the nature and rate of the divergent motion that can be expected in the case of an unbalanced thrust failure on a given airplane in a given initial flight condition substantially reduces the element of surprise and thereby /62
contributes to timeliness and correctness of the countermeasures taken by the pilot.

It should be noted that the very nature of the movements made at the controls to counter the divergent motion of the airplane, and especially the bank that follows failure of a lateral engine, differs to some degree from the customary and usual, when directional motion is controlled with the rudder and transverse motion with the ailerons.

The reason for this is that, as we noted above, the basic cause of the roll of a transversely stable airplane after failure of a lateral engine is the slip that this failure generates.

Hence it follows that the basic element in counteracting the banking of an airplane after failure of a lateral engine must be the effort to counter the slip. Confronted with an unexpected banking of the airplane (which is, as we see, the usual manifestation of an engine failure), the pilot must, as he uses the ailerons, keep the airplane from rolling further by a vigorous deflection of the rudder pedal for the opposite direction.

This reaction does not quite conform to the above-stated requirement of the airworthiness standards ("not to be in contradiction to the customary piloting procedures"), and may not strike the pilot as particularly natural, since he may simply not notice the yawing motion that is in this case the first cause of the roll against the background of the much sharper banking motion. However, to deal with the roll "naturally," i.e., simply by deflect- /63
ing the ailerons, would be incorrect in this case, since deflection of the ailerons has no direct effect in adjusting the slip angle and, as a rule, cannot cancel the transverse-stability moment $M_x = m_x^{\beta}\beta l S\frac{\rho V^2}{2}$ that appears as an effect of slip on lateral-engine failure.

The above does not, of course, mean that the ailerons should not be used at all to counter the roll in such a situation. Deflecting them does produce a certain moment about the longitudinal axis. But, more than that, it is with the ailerons that the airplane is rolled back slightly in the opposite direction — toward the running engines — after the original rolling divergence has been corrected (the expediency of this will be demonstrated below).

However, the most important thing at the first instant is to counteract the first cause of the roll, i.e., the slip, which should be corrected by using all means available to the pilot: both the ailerons and the rudder.

There is only one exception to this recommendation: failure of an engine in the range of Mach numbers in which the reverse rolling reaction to slip prevails. In the presence of the reversed reaction, deflection of the pedal on the side opposite to the bank will not correct it, but will, to the contrary, aggravate it. But, as we know, transverse static stability is small in absolute magnitude in this range of Mach numbers and, consequently, the bank caused by the slip cannot be so sharp as to require a frantic response from the pilot.

Finally, we may not overlook the fact that failure of one of the engines, irrespective of its asymmetry, also causes a decrease in the actual amount of thrust developed. The disturbed equilibrium of the forces acting on the airplane along its longitudinal axis will give rise to a negative longitudinal acceleration (deceleration). If, therefore, the airplane is flying without an adequate excess of its actual speed over the safe maneuvering speed, *measures must be taken quickly to prevent loss of speed:* the pilot must reduce his climbing angle or (if his altitude margin is large enough) even nose the airplane down temporarily until the airplane has been trimmed for partial and unbalanced thrust, or else increase the thrust of the remaining running engines. In taking the last of these measures, it should be remembered that the deficiency of thrust is compensated by increasing the degree of its imbalance (see Chapter III). On multiengined aircraft, therefore, it is advisable to begin the thrust buildup with the engines on the same wing as the out engine, and, most importantly, to add thrust in all cases only after the airplane has recovered from the bank or, even better, been put into a slight bank toward the running engines.

Failures of different engines of the same airplane do not result in identical changes in the airplane's behavior. Naturally, failure of an outboard engine, one situated on a longer arm relative to the plane of symmetry, will be felt more strongly than failure of an inboard engine. On propeller-driven aircraft, even when the arms are equal, failure of an engine on the side away from the direction of propeller rotation will have stronger effects. To take such facts into account, a critical engine can be identified on each airplane as the one whose failure will result in the most unfavorable changes in the airplane's behavior. In evaluating the divergent motion of an airplane after failure of a lateral engine — whether mathematically, with the aid of simulators, or in flight tests — the assumption that precisely this critical engine has failed should consistently be used as the basis. /64

Chapter III /65

STEADY FLIGHT WITH PARTIAL AND UNBALANCED THRUST

1. CHANGES IN THE FLIGHT CHARACTERISTICS OF THE AIRPLANE IN FLIGHT WITH PARTIAL THRUST. RANGE OF SPEEDS, RATE OF CLIMB, CEILING

When it has succeeded in correcting the divergence caused by failure of a lateral engine by counteracting the yawing and especially the rolling motions, and the airplane is being kept from assuming a dangerous attitude, the crew still faces the following problem: continue the flight with partial and unbalanced thrust to the destimation, or at least to the nearest airport (which may also be the airport of departure).

The design case usually chosen in this situation, for any stage in the flight beginning with the climb, is failure of one engine of a two-engined airplane or failure of two engines on aircraft whose powerplants consist of three or four engines or more. If $n \geq 4$, continuation of the flight after failure of two engines on the same side of the airplane's plane of symmetry is considered.

Flight experience confirms the soundness of selection of this case as the design case.

Although we considered failure of only one engine in our investigation of the airplane's divergent motion immediately after development of the thrust imbalance, since failure of a second engine during the short period of time required to bring this divergent motion under control was practically improbable, it is necessary in examining continuation of steady flight with a powerplant not in full working order to base the analysis on the probability of failure of a second engine not within the next few seconds, but within the time needed to complete the flight, i.e., within tens of minutes to several hours. To disregard altogether the possibility of failure of a second engine of an aircraft with /66 $n \geq 3$ engines for this span of time is no longer possible, no matter how improbable this event is statistically.

Failure of more than two engines on the same flight of a modern multiengined airplane is a negligibly rare phenomenon. True, even such cases have been recorded. Thus, in September of 1962, an American C-69 aircraft with 76 passengers aboard went down in the Atlantic after three of its four engines had failed. Even in this case, however, it was not proven that the failure of the three engines was a coincidence and that the events were mutually independent.

Two kinds of difficulties may have to be overcome to continue steady flight with partial and unbalanced thrust after failure of some of an airplane's engines: firstly, inadequacy of the remaining thrust (power) margin and, secondly, the impossibility (or limited possibility) of lateral balancing of the airplane in the presence of the permanent yawing moment from the thrust imbalance.

It was shown above that, as a rule, thrust deficiency and imbalance go hand in hand from the moment of their first appearance. This relation also persists under the conditions of steady flight. Thus, the rudder deflection necessary to counter the unbalanced thrust moment results at the same time in an increase in aerodynamic drag and thus further lowers the already limited thrust margin. On the other hand, complete or partial restoration of the initial thrust by increasing the speed of the running engines increases the imbalance with which it is applied to the airplane.

However, despite this obvious relation, it is expedient in the interests of consistency of exposition to examine the influence of a thrust deficiency on steady flight of the airplane separately from the effects of thrust imbalance.

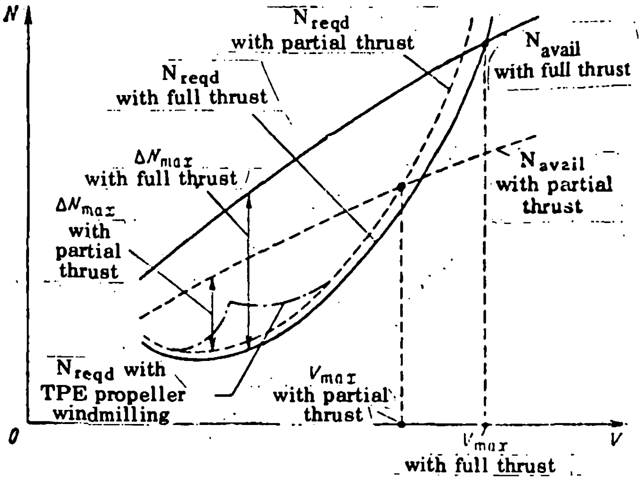

Figure 31. Available and Required Power Curves for an Aircraft in Flight with Full and Partial Thrust.

Figure 31 shows schematic required and available power curves for a certain airplane. Top speed in level flight corresponds to the point at which these curves intersect, at which the required power equals the available power (unless, of course, there is a Mach-number or ram-pressure limit to top speed).

Maximum rate of climb is obtained at the speed corresponding to the maximum power margin, i.e., to the greatest distance along the axis of ordinates between the curves of available and required power for the particular altitude.

The region included between these curves is that of possible /67
level-flight regimes. In partial-thrust flight, the required and available power curves are shifted as indicated by the dashed lines in Fig. 31. This shift needs no explanation: it is natural that failure of some engines lowers powerplant output proportionally. Figure 31 shows the change in the trend of the available-power curve for the case in which one of four engines on the airplane is

out. Thus the ordinate of each point on the dashed curve represents 0.75 of the corresponding ordinate of the solid curve.

Simultaneously, the required-power curve changes its position slightly, moving upward. This shift has several causes: the rudder and aileron deflections to counter the yaw and roll, the increased drag of all parts of the airplane as a result of the oblique wash (if the flight continues without elimination of the slip), and, finally, the aerodynamic drag of the failed engine itself and its propeller. As we pointed out above, the latter is especially large if the airplane has turboprop engines and for some reason it has not been possible to feather the propeller of the failed engine. For these reasons, the aerodynamic drag of the airplane increases and, accordingly, so does the power required to fly it. As a result, the region of possible level-flight regimes in flight with partial and unbalanced thrust (the /68 region between the dashed curves in Fig. 31) is narrowed appreciably and the flight performance of the airplane deteriorates accordingly.

Thrust deficiency has a lesser effect on the range of flight speeds of which modern jet aircraft are capable. In any event, this range is reduced to a substantially lesser degree than rate of climb and ceiling for aircraft with gas-turbine engines. This peculiarity is explained by the fact that the top speed of a jet airplane, unlike those of the propeller aircraft of past years, is not always limited by powerplant output, and, if it is, then not at all altitudes.

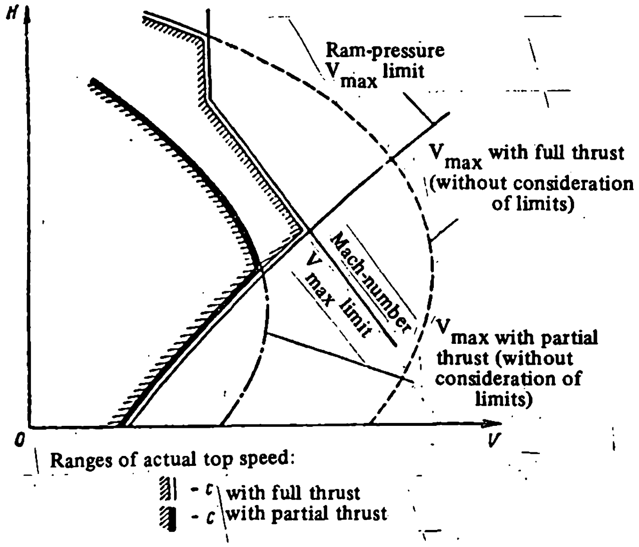

Figure 32. Range of Possible Flight Speeds of a Jet Airplane vs. Altitude with Full and Partial Thrust.

Figure 32 presents a diagram of the top speed of a jet airplane against altitude. The dashed curve indicates the top speed that the airplane could develop in level flight at nominal (maximum) powerplant output on the assumption that there are no restrictions in the way of reaching this speed.

In actuality, however, such limitations do exist, both in the ram pressure $q = \rho V^2/2$ and in the Mach number. Exceeding the ram-pressure restrictions would result in the exertion of excessive, above-design forces on the airplane by the airstream and would be inadmissible from the standpoints of the static and dynamic strength and the rigidity of its construction. Exceeding the Mach-number restrictions, on the other hand, would result in the development of shock-stall phenomena and the associated stability and controllability crisis, in which the airplane may nose down into a dive, roll spontaneously ("list"), go into buffeting-type vibrations, and exhibit other undesirable effects. /69

Figure 32 illustrates Mach-number and ram-pressure flight-speed limitations. Because such limits exist, the practically attainable top speed is found to be considerably lower than the speed corresponding to full utilization of powerplant output. In a wide range of altitudes – from the ground to the altitude corresponding on the diagram to the point at which the dashed top-speed curve for full thrust crosses the curve of the ram-pressure and Mach-number limits – the highest possible top speed is maintained on partial thrust, with the powerplant throttled back, regardless of its working order.

The dot-dash curve on the same figure indicates the line of top speeds for forced flight with partial thrust (the case in which the deficiency is due to failure of some of the engines). In a certain altitude range, this curve, which lies quite far to left of the dashed full-thrust top-speed curve, runs to the right of the limit line. In this range, which extends from the ground to five or six kilometers or more for modern aircraft, the airplane will therefore have a thrust, even with not all of its engines running, sufficient to develop a speed in excess of the imposed limits or at least approaching them. In such a case, failure of some of the engines will have little or no effect on the range of speeds.

The thrust deficiency will have a much stronger effect on the airplane's rate of climb (vertical velocity), which, of course, is determined by the formula

$$V_y = 75\frac{\Delta N}{G},$$

where V_y is the rate of climb in m/sec, G is the weight of the airplane in kg, and ΔN is the power margin in hp.

It is evident from this formula that the rate of climb depends directly on power margin, which, being a comparatively small difference between two large quantities (N_{avail} and N_{req}), is highly sensitive to changes in them.

As a result, if the top speed of the airplane is lower by only 10-20% after failure of 25-50% of its gas-turbine engines, its vertical velocity drops by a large factor (5-8). /70

The turbojet engines of present-day aircraft are not characterized by high high-altitude performance. All other conditions the same, their thrust (power) diminishes steadily with increasing altitude. The rate of climb of the aircraft also decreases accordingly.

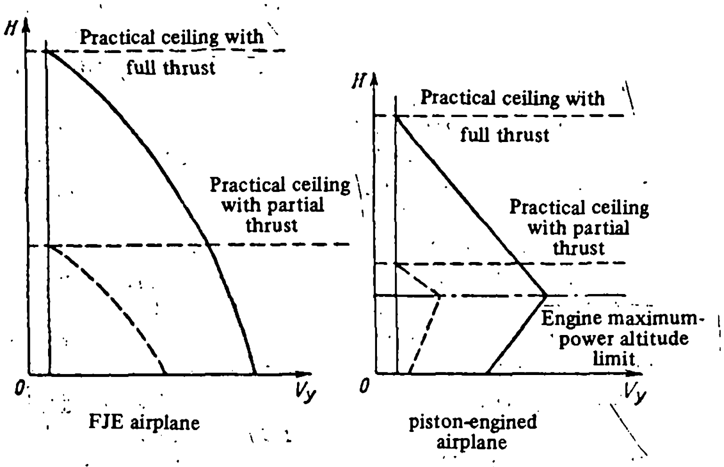

Figure 33. Vertical Velocity V_y as a Function of Flight Atltitude H and Ceiling H_{max} for Aircraft with Turbojet and Piston Engines Developing Full and Partial Thrust. Solid lines: full thrust; dashed lines: partial thrust.

Since, as we have shown, the rate of climb at each given altitude is substantially lower in flight with partial thrust than in full-thrust flight, the airplane's ceiling in the former case will correspond to a considerably lower altitude than in flight with the powerplant in full working order (Fig. 33).

The effect of partial thrust on ceiling is even more pronounced for piston-engined aircraft, whose ability to climb is usually exhausted at an altitude only a few hundred meters above the maximum-power altitude.

What we have said concerning the change in the performance of gas-turbine-engined aircraft in flight with partial thrust is, of course, generally valid also for aircraft with turboprop engines, but only provided that the propellers of the out engines are feathered. If, on the other hand, the feathering system does not function properly and the propeller of the failed turboprop engine /71 continues to turn by autorotation, the trend of the required-power curve changes significantly owing to the drag generated by the propeller. As a result, the range of possible level-flight regimes is reduced even further.

While they are capable of reliable level flight in a broad range of altitudes, and even of climbing with not only one but even with two engines out if their propellers are feathered, most four-engined turboprop aircraft are hardly capable of level flight even with one engine out if its propeller is windmilling.

As was shown in Fig. 26, the propeller drag of a windmilling turboprop engine is different at different flight speeds. It reaches its maximum at the boundary between the speed range in which the propeller turns at constant rpm and the range corresponding to rotation on the stops, i.e., at a constant setting angle. At lower speeds, the drag of the windmilling propeller decreases smoothly, and at higher speeds it also decreases, but even more sharply, tending rapidly to a certain practically constant rather low value.

This behavior of the aerodynamic-drag curve of a windmilling propeller with varying speed explains the specific shape of the required-power curve (see Fig. 31) characteristic for turboprop aircraft with the propeller of a failed engine windmilling.

If the speed in the optimum regime corresponding to the largest power margin for the particular aircraft in flight with full thrust is near the speed at which the windmilling propeller has maximum drag, the optimum flight regime with partial thrust and a windmilling propeller will naturally be shifted toward somewhat lower flight speeds than when the propeller of the out engine has been feathered. Needless to say, the power margin is found to be much smaller in absolute magnitude in the windmilling-propeller case.

Figure 33 shows the altitude variations of rate of climb for aircraft with jet and piston engines. These curves are similar in trend to those representing the power (thrust) variation inherent to engines of these classes. The piston engine has a supercharger or turbocharger that ensures maintenance and even a slight increase of its power output as the airplane climbs from the ground to its maximum-power altitude. The power output of gas-turbine engines (except for the fanjet) does not, as we stated above, increase with altitude.

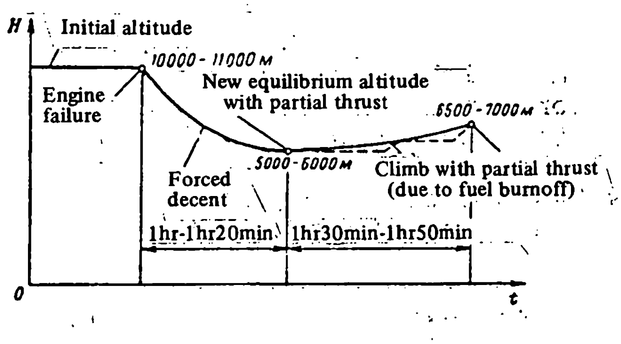

Figure 34. Flight Profile of Tu-104 Aircraft after Failure of One Engine.

In partial-thrust /72 flight, this difference has one practically highly important consequence: if for a certain piston-engined aircraft under certain specific conditions (aircraft weight, ambient-air temperatures, rpm of windmilling propeller) the power margin does not support level partial-thrust flight near the maximum-power altitude, there is no reason to expect that this will become possible at some lower altitude.*

Turbojet aircraft, whose thrust and power margins increase steadily with the approach to the ground, are another matter. Thus, even if the airplane cannot fly level at high altitudes with partial thrust, the appearance of this capability at some lower altitude is not excluded. Thus, the Tu-104 can fly normally at full weight on one engine at altitudes up to five or six thousand meters. If it sustains an engine failure at a higher altitude, the airplane must inevitably descend, but this process will take place quite slowly, and at variable vertical velocity (which decreases as the airplane descends closer to the new equilibrium altitude corresponding to the partial-thrust ceiling). Having descended to this altitude, the airplane will become able to climb again after a certain time as it burns off fuel and its weight diminishes accordingly (Fig. 34).

In practice, of course, it is not always possible to follow this profile. If the airplane is flying in an airway zone, where /73 safety considerations require strict observance of vertical separation, the crew of the airplane whose engine has failed will be obliged to continue the flight not on an inclined trajectory, but along a certain stepped profile (this profile is indicated by the dashed line in Fig. 34), in which each successive step corresponds to the highest level of flights in the particular direction at which partial-thrust flight is possible at the given aircraft weight. The airplane remains on this level until the weight loss resulting from burnoff of fuel permits it to climb to the next more favorable level.

At first glance, the forced altitude change after partial powerplant failure may not appear hazardous, but it may sometimes give rise to significant difficulties. Thus, if prior to failure of one of its engines, the airplane was flying above clouds characterized by icing conditions, strong turbulence, or other dangerous phenomena, partial powerplant failure would involve a forced change to an altitude at which these dangerous phenomena would inevitably be encountered.

To avoid the need for repeated trial climbing after a partial engine failure to attain the altitude at which level flight can be continued under the particular conditions and at the particular flight weight, these quantities are determined in advance during the flight tests of each airplane. The data thus acquired are reduced to diagrams (nomograms) from which the crew can, at any time, knowing the weight of the machine, the ambient-air temperature, and the other necessary parameters, determine the altitude range in which continuation of level flight is possible and ask permission to change to the new level at the appropriate time.

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*In this case, we speak of the lower of the existing maximum-power altitude limits, at which the power of an engine having a geared supercharger with several speeds (transmission ratios from the engine shaft to the supercharger shaft) is at maximum.

2. FLIGHT RANGE WITH PARTIAL THRUST

Other conditions the same, the flight range of an airplane is determined by its per-kilometer fuel consumption q_k. For turbojet-engined aircraft,

$$q_k = C_e G/3.6VK,$$

where C_e is the specific fuel consumption in kg of fuel per kg of thrust per hour, G is the airplane's flight weight in kg, V is its true (air) speed in km/h, and K is its lift-drag ratio.

Consequently, the longest range will correspond to the largest value of the product V · K.

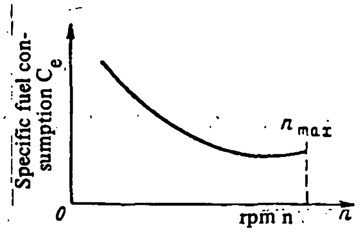

Figure 35. Specific Fuel Consumption C_e as a Function of Turbojet-Engine rpm.

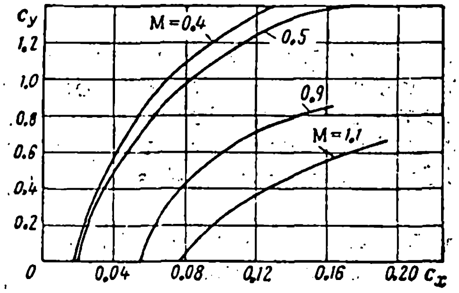

Figure 36. Polar Curves of Aircraft for Various Mach Numbers.

Calculations indicate that the maximum value of this product /74 is attained in the regime corresponding to $c_y \cong c_{yk_{max}}/\sqrt{3}$, at which the lift-drag ratio is about 87% of its maximum value. However, the loss in lift-drag ratio is offset by the gain in flight speed.

Thus, turbojet aircraft have their maximum flight range in regimes much closer to their top-speed regimes than do piston-engined aircraft, whose maximum range is obtained in flight at an angle of attack near the optimum.

On a descent to a lower altitude with retention of the same angle of attack (which corresponds to the lift-drag ratio established above, the optimum from the range standpoint), a loss of flight range is inevitable.

The cause of this loss is dual in nature. Firstly, range is shortened owing to the lowering of flight speed in denser air. Secondly, with the transfer to the lower altitude, the specific fuel consumption C_e increases as a result of the fact that the same thrust needed for flight at the angle of attack corresponding to $(VK)_{max}$ will be obtained at lower rpm (engines throttled back farther) at the lower altitude. Figure 35 shows a typical curve of specific consumption vs. turbojet-engine rpm.

On the other hand, a useful effect does arise on transfer to the lower flight altitude with retention of the original angle of attack — a more favorable trend of the polar curve owing to the decrease in the Mach number, i.e., the distance between the actual flight regime and the shock-stall range. Figure 36 shows several polar curves of the same aircraft for various M. We see from the /75 figure that the absence of wave drag markedly lowers the c_x of the airplane as a whole. However, calculations that have been borne out in practice indicate that with the decrease in altitude, the sum effect of the unfavorable changes in speed and specific fuel consumption outweighs the helpful influence of the Mach-number change.

As a result, aircraft with turbojet engines attain their longest ranges at the highest altitude at which the thrust of the powerplant in operation at the highest output permitted for continuous duty supports flight at the angle of attack corresponding to a lift-drag ratio $K \cong 0.87K_{max}$ [19].

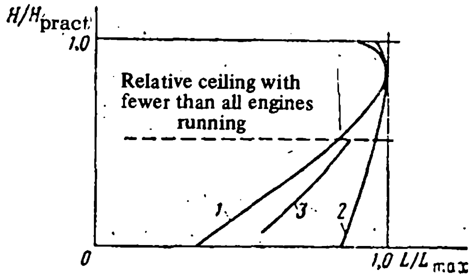

Figure 37. Variation of Flight Range with Altitude for Aircraft with Turbojet and Piston Engines. 1) Turbojet-engined aircraft; 2) piston-engined aircraft; 3) turbojet aircraft at partial thrust.

As a rule, this altitude is 1-3 km below the practical ceiling of modern jet aircraft. It is at this altitude that most route and cruise flights are made.

It is easy to conclude from the above that a forced descent due to partial powerplant failure has a negative effect on flight range. In certain cases, the range loss that occurs here may make it necessary to return to the departure airport (if the failure took place on the first half of the distance) or even to make a forced landing at an intermediate airport.

In changing altitude after failure of one or more engines, therefore, the rule is that the airplane's crew must review the flight plan with consideration of the change in range and apply the necessary corrections to it.

Figure 37 shows the relative loss of range on leaving the optimum flight altitude for aircraft with various types of engines. However, it must be remembered in evaluating the relationships illustrated in the figure, especially as regards TJE aircraft, that curves 1 and 2 were plotted on the assumption that all engines on the airplane are in use at all altitudes, i.e., they assume transfer to the lower altitude with correspondingly reduced rpm and, consequently, higher specific fuel consumption.

If, however, we are concerned with a forced descent related to partial engine failure, it must be assumed that the engines that remain running will be operated at the same settings as before the engine failure or even at higher settings in order to deliver the necessary total powerplant thrust. Consequently, it is not necessary to expect losses due to the increase in the specific consumption C_e, and therefore, as shown by curve 3 of Fig. 37, the range losses will also be somewhat smaller. /76

The research of M.I. Mazurskiy and other authors has shown that under certain conditions, shutdown of 50% of the powerplant may not only not reduce the original range, but even lengthen it (up to 10-15%) and the airplane's endurance (up to 20%) because of the markedly lower flight speed. If, however, the speed is not of decisive importance under the particular concrete circumstances, transition to flight with some of the engines shut down deliberately may even prove helpful, especially for heavy aircraft with large values of the ratio $G_{fuel}:G$ (0.5 and more). In any event, the question as to the possibility of reaching the destination airport — regardless of the time involved — is easier to answer in the affirmative.

It must be remembered, however, that the above pertains to the case of flight with the powerplants used in different ways at a given altitude. However, as concerns the absolute maximum range attainable by a certain type of airplane with a certain fuel reserve and a certain flight weight, this range is attained, as we noted above, with all engines in near-nominal operation, and in flight 1-3 km below the practical ceiling. Shutdown of some of the available engines — and it makes no difference whether this is intentional or forced — makes it necessary to go to lower altitudes and, consequently, results in a range loss as compared with the maximum possible range value.

3. FLIGHT CONDITIONS ONE AND TWO ON AIRCRAFT WITH PISTON, TURBOJET, AND TURBOFAN ENGINES. FLIGHT WITH PARTIAL AND UNBALANCED THRUST IN CONDITIONS ONE AND TWO

Failure of one or even two engines of a modern aircraft with a high thrust-weight ratio in level flight does not always mean that it is necessary to descend. Moreover, flight can be continued at the altitude of the failure in many cases, but at an appropriately lower speed.

Hence arises the question as to the minimum speed that the pilot must reach if he has advance knowledge of neither the equilibrium speed under the new conditions nor the very possibility of continuing flight with partial thrust at a particular altitude. It will be shown below that the lowest permissible speed in this case corresponds to the boundary between flight conditions one and two. On the other hand, lowering the speed further to stalling speed (which corresponds to the critical angle of attack) or even to the safety speed is, firstly, of no help, since it would result in a transition into a range in which the negative power margin increases again (a change in the sign of the gradient $\partial(\Delta N)/\partial V$), and, secondly, is not without its hazards, since it would make handling difficult.

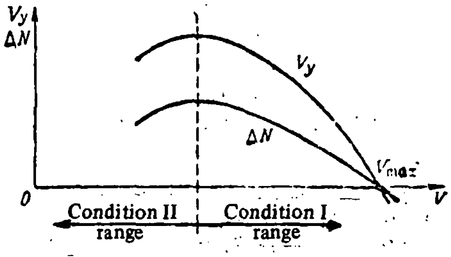

Figure 38. Power Margin ΔN and Vertical Velocity V_y vs. Forward Speed V (at Constant Powerplant Setting). /77

The division of the range of flight speeds into condition-one and condition-two segments has long been customary in aerodynamics, but with the advent of jet aircraft the practical importance of this division, especially when the dynamics of partial-thrust flight are considered, has increased substantially.

Flight conditions one and two are characterized by opposite relationships between the variations of forward speed and the corresponding variations of vertical velocity (Fig. 38). In condition one, the vertical velocity is lower the higher the forward speed up to V_{max}, at which $V_y = 0$. In condition two, on the other other hand, vertical velocity is higher the higher the forward speed.

In most existing textbooks on flight theory, condition two is evaluated as unfavorable from the standpoint of economy, since it is characterized by higher required-power values and, consequently, increased fuel consumption rates without any speed gain.

However, it is helpful to analyze condition two flight from the standpoint of its inherent piloting characteristics.

As we see from Fig. 39, a decrease in speed at a given power plant setting in condition I flight (region A) results in an

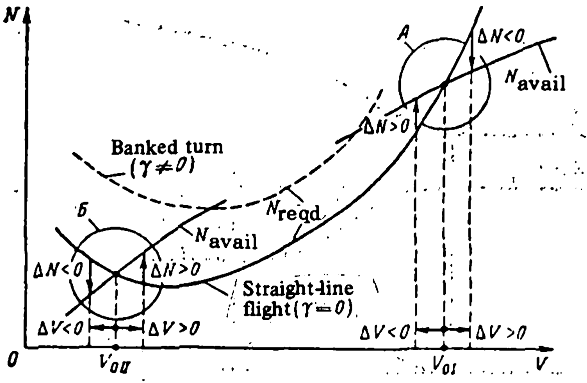

Figure 39. Required and Actual Thrust Curves of an Airplane. A) Range of condition I flight; B) range of condition II flight.

increase in power margin. It is essentially on this relationship that the generally accepted technique for control of an aircraft in pitch is based: a decrease in forward speed for climbing and an increase for descent. In principle, an automatic pilot with altitude correction (by means of a statoscope) also controls an airplane in the same way.

However, this state of affairs, which is the natural one for the pilot and the one to which he is accustomed, breaks down in condition two, in which the slopes of the required- and actual-power curves change sign (region B). Here a decrease in speed results in a /78
drop in the power margin and, consequently, the beginning of a climb rather than a descent.

It may seem at first glance that this reversed $\Delta N = f(\Delta V)$ relationship would be manifested so obviously that it could not escape the pilot's notice.

Actually, however, this behavior is masked by another effect — a redistribution of the kinetic and potential components of the airplane's total energy. As a result, a decrease in speed at constant powerplant setting always gives rise initially to a g-force $n_y > 1$ and a corresponding increase in vertical velocity (i.e., if the initial flight condition was level flight, transition to a climb) owing to conversion of some of the kinetic energy into potential energy. Conversely, a speed increase always results in the initial instant in a decrease in V_y (transition from level flight to descent) owing to conversion of some of the airplane's potential energy to kinetic energy.

Hence the true pattern of the change in parameters in transitional flight conditions is found to resemble that shown in Fig. 40. When the new speed value $(V - \Delta V)$ has been established, a new vertical velocity will also have been established: a positive one in condition one (Fig. 40a) and a negative one in condition two (Fig. 40b). In the intermediate stage, however, during the unsteady motion, a decrease in speed will produce the same effect in either of these cases: transition to a climb, no matter how brief in duration.

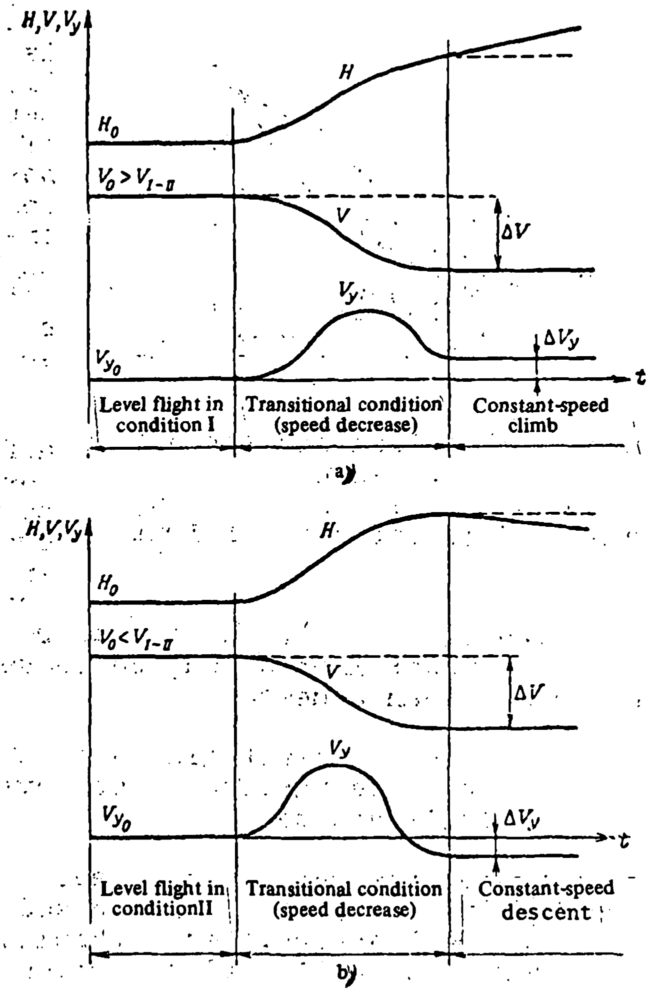

Figure 40. Transitional Flight Regimes During Correction of a Deviation from Assigned Altitude. a) In the condition I range; b) in the condition II range.

The effect of kinetic and potential energy component redistribution is especially strongly manifested on modern high-speed airplanes, which have such a /79 large kinetic-energy margin that even a relatively small change in this energy will result in an appreciable change in altitude.

Thus, if, without changing the positions of the throttles, the pilot of a subsonic jet airplane with swept wings and a wingload on the order of 400-420 kg/m^2 reduces his speed by 20 km/hour in an initial condition of level flight at an altitude of 10,000 m at an /80 indicated speed of 385 km/hour (these conditions correspond to condition two flight), the airplane will gain about 200 m of altitude as a result of conversion of some of its kinetic energy into potential energy.

As we have noted, however, this climb will be temporary. After the new speed value has been established, the airplane will no longer be able to fly level, since it is even deeper into the condition-two range, where the power margin is negative. As a result, the airplane will go into a descent at a vertical velocity of about 0.4-0.5 m/sec. As it descends, it will again cross the altitude at which the maneuver was started and continue the descent even further. However, it is easily calculated that the descent to the starting altitude will, under these conditions, take 6-8 minutes. At the end of this time interval, the pilot will hardly be able to recognize the relation between the descent and the speed change that he undertook earlier.

A similar situation may arise in the event of failure of one engine at an altitude higher than the ceiling of the airplane at the remaining thrust. Let us assume that the pilot does not know this new value of the ceiling and attempts to hold his original altitude by the usual, natural method — by pulling back on the stick and lowering speed accordingly. At first, he will succeed in holding to the level trajectory by using up the kinetic-energy reserve. However, the attempt to utilize all of this reserve will inevitably result in a loss of speed. Therefore, if the pilot does not know precisely in advance whether or not level flight will be possible at the particular weight with partial thrust at the altitude at which the engine failed, he should permit loss of speed only to the point corresponding to the boundary between conditions I and II. If, even on reaching this speed, the airplane is not balanced in horizontal flight, it remains for him to descend, maintaining this speed, to the altitude at which the vertical velocity vanishes of itself.

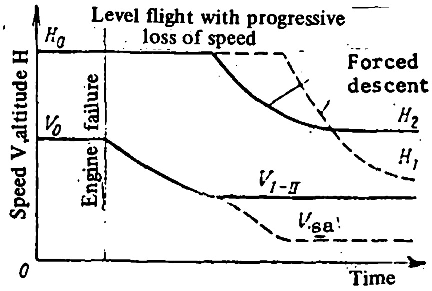

Figure 41. Descent of Airplane After Failure of One of its Engines at the Safety Speed V_{sa} and at the Speed V_{I-II}, Which Corresponds to the Boundary Between Flight Conditions One and Two. V_0) Speed before powerplant failure; H_0) altitude before powerplant failure; V_{sa}) safety speed; V_{I-II}) speed corresponding to boundary between flight conditions I and II; H_1) new ceiling in partial-thrust flight at safety speed; H_2) New ceiling in partial-thrust flight at speed corresponding to boundary between flight conditions I and II.

The maximum possible power margin (or, more properly, the smallest absolute negative power margin) is built up in this type of descent. The vertical velocity will then be the smallest possible and, consequently, the ability of the airplane to fly level is restored at an altitude higher than in any other descent regime.

Figure 41 shows two variants of the forced descent of an airplane after partial powerplant failure. In one case, the airplane has been permitted to decelerate at the initial altitude only to the speed corresponding to the boundary between conditions one and two; in the second case, speed has been lost down to the safety level. As we /81 see from the figure, the forced descent takes place at a higher vertical velocity in the latter case, and the airplane's ability to continue level flight is restored at a much lower altitude than in the first case.

It must also be remembered that after attainment of the speed corresponding to the boundary between conditions one and two, the subsequent deceleration speeds up sharply: on entering the condition-two range, the airplane comes under the influence of a sharp increase in its power deficiency (negative power margin). Under such conditions, diversion of the pilot's attention to other flight procedures, navigation, powerplant control, etc., which naturally becomes more probable immediately after an unexpected engine failure, may result in total loss of airspeed and a stall.

Consequently, even a moderate decrease in speed below the boundary between conditions I and II is equally inadmissible both from the standpoint of retention of the best possible flight performance and from the standpoint of flight safety.

The above is especially important in partial-thrust flight, when the available power margin is down sharply and, as a consequence, return to the range of flight condition one after an accidental entry into condition two is much more difficult.

Thus, the value of the speed V_{I-II} corresponding to the boundary between flight conditions I and II is a highly important quantity for piloting, especially in flight with partial and unbalanced thrust. Naturally, the question as to the position of its boundary arises.

As was shown in Fig. 39, the decisive difference between conditions I and II is that the slopes of the required- and available- (actual-) power curves bear opposite relations to one another.

In condition one $\partial N_{reqd}/\partial V > \partial N_{avail}/\partial V$, and in condition two $\partial V_{reqd}/\partial V < \partial N_{avail}/\partial V$. /82

Hence it follows that the slopes of the required- and available-power curves should be the same at the boundary between conditions one and two. However, this condition is met not at their intersection, but only at their point of tangency, or, more precisely, where the required-power curve touches that curve of the family of available-power lines that occupies the lowest position in that family and does not cut the required-power curve at two points, touching it at only one point.

For aircraft with engines of a given class, it is possible to establish the position of this point for the general case, without resorting in each particular case to construction of the family of available-power curves and its superposition onto the required-power curve. Thus, the available-power curves corresponding to various throttle-lever positions for piston-engined aircraft run almost horizontally, and the sought point of tangency is near the condition corresponding to the smallest required power, which, as we know, is attained at the economy angle of attack α_{ec} (Fig. 42).

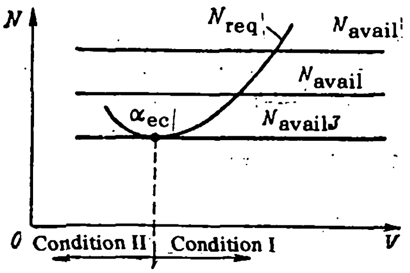

Figure 42. Illustrating Location of Boundary Between Flight Conditions I and II for a Piston-Engined Airplane.

For turbojet aircraft, power at constant rpm is practically proportional to speed, since N = PV,* and the required-power curve is a straight line segment drawn from the origin of the N = f(V) diagram. Naturally, this curve is tangent to that curve of the N_{avail} family that has the smallest slope angle ϕ. As we see from Fig. 43, the tangent of ϕ is numerically equal to the power-speed ratio, i.e., to engine thrust:

$$\operatorname{tg}\varphi = \frac{N}{V} = P.$$

In other words, the smallest slope will be attained at minimum thrust, i.e., in flight at the optimum angle of attack and the maximum lift-drag ratio K. /83

Consequently, the boundary between flight conditions one and two corresponds to the economy angle of attack for a propeller-driven airplane and to the optimum angle of attack for a jet airplane.

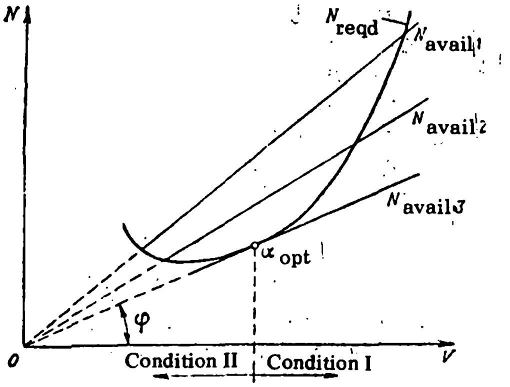

Figure 43. Illustrating Location of Boundary Between Flight Conditions I and II for an Airplane with Turbojet Engines:

$$\varphi_{\min} \sim \left(\frac{N}{V}\right)_{\min} \sim P_{\min}$$

In practice, however, flight at angles of attack exceeding the economy value is almost never entered intentionally owing to the proximity of this angle to the maximum permissible value. On the other hand, all types of airplanes are flown much more often at attack angles near the optimum, especially at high altitudes, and certain types, such as those lacking horizontal tailplanes and having small-aspect-ratio wings without flaps — the Tu-144 (USSR), the "Concorde"

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*Thrust varies little in the speed range of interest to us (for most turbojet-engine types, it remains within 1.5-3% of its average value at cruising speeds, flight altitudes of 10-12 km, and airspeeds from 300 to 500 km/h).

(France and England), the "Drakon" (Sweden), and others – are even landed at such angles. It is therefore considerably more probable that a jet airplane will be flown in a range approaching condition II. This applies in particular to the flight of jet aircraft with partial thrust, when the effort to make the most efficient use of the remaining thrust forces the pilot to make directly for this flight condition, which is the optimum from that point of view.

4. POSSIBLE STEADY-FLIGHT REGIMES WITH UNBALANCED THRUST. SLIPPING FLIGHT WITHOUT ROLL /84

A second set of problems related to the continuation of steady flight after partial powerplant failure is concerned with balancing the aircraft in yaw and roll, i.e., compensating the moments that arise in such cases. Without solution of this problem, further flight is impossible even if the thrust remaining at the pilot's disposal is adequate to overcome the aerodynamic drag.

Such a situation may arise, for example, when the engines are located far abeam of the airplane's center of gravity and rudder effectiveness is simultaneously inadequate.

In the absence of a forward velocity, the moment that arises on failure of one of the engines of a VTOL aircraft whose engines are comparatively far outside of the airplane's plane of symmetry can be countered either by the use of jet or gas vanes, which do not usually have large effectiveness margins, or by cutting off (or reducing appropriately) the thrust of the failed engine's counterpart on the opposite side, although this naturally results in an additional loss of total thrust.

In this book, we shall confine ourselves to analysis of yaw and roll balancing in unbalanced-thrust flight of conventionally configurated aircraft in normal flight with a forward velocity.

Flight crews generally regard this problem as less complex than that of countering the divergent motion that follows immediately upon an engine failure.

Generally speaking, there are certain grounds for this point of view, at least in that it takes account of the element of surprise, which, as we know, is by itself probably the most dangerous factor. Even in steady flight, however, roll and yaw balancing of the airplane may involve certain complications.

First of all, it must be remembered that the absolute value of the unbalanced-thrust moment acting on the airplane in steady flight may differ from that which appeared at the instant of lateral-engine failure. This is because it is generally necessary to increase the thrust of the running engines after such a failure to maintain all or at least most of the initial flight speed, and to do so in such a way that the total thrust of the engines will

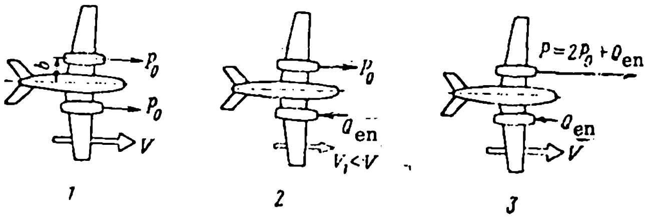

Figure 44. Increase of Unbalanced-Thrust Moment $M_{u.t}$ After Failure of One Engine: 1) Initial situation – balanced-thrust flight at speed V, yawing moment $M_y = 0$; 2) starboard engine has failed, and a yawing moment $M_y = (P_0 + Q_{en})b$ has appeared; 3) steady flight with unbalanced thrust at initial velocity V, yawing moment $M_y = (P + Q_{en})b = 2(P_0 + Q_{en})b$; P_0 is the thrust of each engine in the initial flight condition with full and balanced thrust; Q_{en} is the drag of the failed engine; P is the thrust of the running engine in steady unbalanced-thrust flight.

remain unchanged or even increase somewhat to overcome the drag of the out engine. This pertains in particular to turboprop aircraft in the event that not only the engine, but also the feathering system fails. Thus, for example, the thrust obtained from each of the three remaining engines on the Il-18 and An-10 aircraft after /85 failure of one must be 50-60% higher than in flight at the same speed with the entire powerplant in working order. Figure 44 shows schematically the increase in the unbalanced-thrust moment in steady flight at the initial speed as compared with the moment that prevailed on failure of one of the engines.

However, exceptions to this rule are possible. Thus, on multiengined aircraft having more than one engine on each side, failure of one of them may be compensated fully or in part in many cases by increasing the thrust of the running engines on the same side of the airplane's plane of symmetry, so that the unbalanced-thrust yawing moment will be, if not cancelled, then at least greatly reduced (Fig. 45). For this, of course, it is necessary that normal flight at the particular altitude with the powerplant in full working order not require full thrust from each engine, so that a certain reserve remains for increasing it.

Control of an airplane in steady flight with unbalanced thrust has a number of aspects to which the pilot is not accustomed, some of which interfere directly with handling of the airplane.

The following are most strongly felt by the pilot:

1) *deflection of the rudder*, in many cases through a substantial part of the available travel;

2) *pedal effort* corresponding to this deflection, although this can be fully eliminated with the trim tabs in steady flight

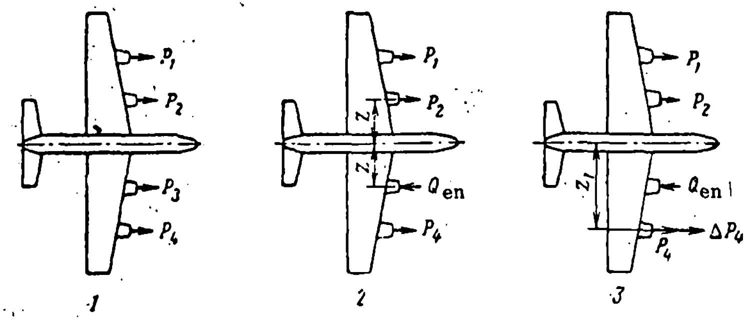

Figure 45. Compensation of Unbalanced-Thrust Moment on a Multiengined Airplane.
1) Initial situation: $P_1 = P_2 = P_3 = P_4$; $\Sigma P = P_1 + P_2 + P_3 + P_4 = 4P$; $M_y = 0$;
2) failure of No. 3 engine: $P_1 = P_2 = P_4$ $\Sigma P = P_1 + P_2 + P_4 = 3P$; $M_y = (P + Q_{en})z$
3) thrust of No. 4 engine increased by $\Delta P_4 = (P + Q_{en})z/z_1$: $P_1 = P_2$; $\Sigma P = P_1 + P_2 + P_4 + \Delta P_4 = 3P + (P + Q_{en})z/z_1$; $M_y = 0$

of almost all existing aircraft; /86

3) deflection (rotation) of the control yoke, sometimes to 90° away from neutral, with the result that certain inconveniences are encountered in operation of the manual controls, the aileron-deflection margin in one direction is reduced, and the view of some of the panel instruments is blocked. The yoke deflection from neutral is especially large for propeller aircraft, failure of one of whose engines gives rise to unbalanced wash of the wing surface.

However, all of these factors complicating the work of the pilot are subject to wide variations depending on how the airplane is piloted in steady flight with unbalanced thrust. Moreover, as will be seen below, the use of various handling techniques may have substantial influence not only on the convenience of control, but also on the airplane's aerodynamic drag and hence on the basic performance data characterizing its flight with partial and unbalanced thrust: speed range, rate of climb, ceiling.

In principle, steady unbalanced-thrust flight can be accomplished in many different regimes, which are characterized by various combinations of the angles of roll and slip. In all cases, /87 however, the following conditions must be satisfied to ensure lateral balancing of the airplane in steady flight:

$$\sum Z=0;\ \sum M_y=0;\ \sum M_x=0,$$

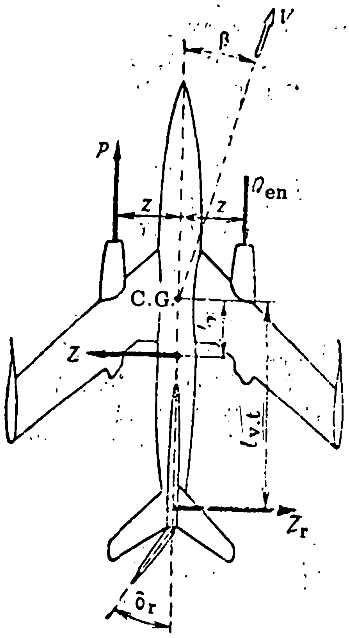

Figure 46. Slipping ($\beta \neq 0$) Unbalanced-Thrust Flight Without Roll ($\gamma = 0$).

or, in equations with dimensionless coefficients,

$$\left.\begin{aligned}
&c_z^{\beta}\beta + c_z^{\delta_r}\delta_r + c_y\frac{\gamma}{57.3}=0;\\
&m_y^{\beta}\beta + m_y^{\delta_r}\delta_r + m_{y\,\mathrm{u.t}}=0;\\
&m_x^{\beta}\beta + m_x^{\delta_a}\delta_a + m_{x\,\mathrm{wash}}=0,
\end{aligned}\right\} \qquad (6)$$

where $m_{y\ u.t}$ is the coefficient of the unbalanced-thrust yawing moment and $m_{x\ wash}$ is the coefficient of the rolling moment from the unbalanced wash over the wings (for propellerless aircraft $m_{x\ wash} = 0$).

The first two equations of system (6) characterize the equilibrium of the airplane in the yaw plane — the same plane in which the symmetry of the operating external forces and moments has been disturbed. These equations are satisfied by various possible combinations of the angles γ and β. Let us consider some of the combinations of greatest practical interest.

Figure 46 shows the unbalanced-thrust flight condition most likely to be used by a pilot without special training for flight under such conditions because it is the most natural.

This condition is characterized by retention of the same spatial attitude of the airplane as before the engine failure, i.e., zero roll.

However, it is easily shown that in this case, in contrast to balanced-thrust flight, zero-roll flight is possible only with slip.

Actually, if we examine the condition for equilibrium of the /88
moments acting on the airplane about its vertical axis, we quickly see that in order to counter the yaw due to application of the unbalanced-thrust moment $M_{u.t} = (P + Q_{en})z$, the pilot must deflect the rudder in the direction of the running engines, thereby creating a moment $Z_r l_{v.t}$ equal in magnitude but opposed in sign to the

unbalanced-thrust moment.

Although it might seem that this would ensure lateral balancing of the airplane, only the moments acting on the airplane about its vertical axis have actually been compensated, and not the transverse forces acting on it. For example, the transverse force Z_r due to deflection of the rudder is at first totally uncompensated. Under the action of this force, the airplane naturally acquires a certain lateral acceleration dV_z/dt, i.e., it begins to move in the direction of the out engine by slipping if not by rolling. As the lateral velocity component V_z increases, a lateral component Z of total aerodynamic drag arises and begins to increase; it will continue increasing until it is equal in magnitude to the lateral force generated by the rudder deflection, i.e., until not only the moments but also the transverse forces acting on the airplane have been brought into balance.

However, since the lateral aerodynamic force Z is always applied not to the center of gravity of a directionally stable airplane, but to a certain point between the airplane's center of gravity and its tail, this force generates, in turn, a moment Zl_1 in the yaw plane, which acts in the same direction as the unbalanced thrust moment and therefore aggravates the effect of the latter.

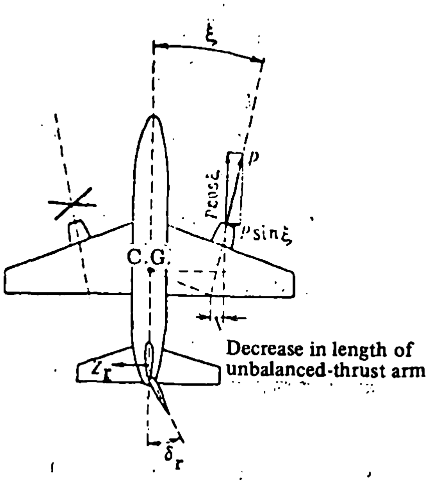

Figure 47. Positions of Lateral Engines Corresponding to Divergence of the Lines of Thrust Action from Flight Path.

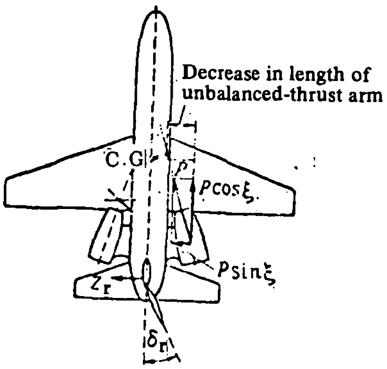

Figure 48. Lateral-Engine Positions Corresponding to Convergence of Lines of Thrust Action to Flight Path.

To counter this additional moment, the pilot must deflect the rudder by a certain amount above and beyond that necessary to counter the unbalanced-thrust moment proper. In turn, this additional rudder deflection will cause some increase in both the lateral velocity component V_z and the lateral aerodynamic-drag component Z. As a result, equilibrium of the forces acting on the airplane in the transverse plane will be attained at somewhat larger values of both of these forces Z_r and Z, and only then will the regime of uniform straight-line nonrolling but slipping flight with unbalanced thrust be fully established, as shown in Fig. 46.

If the engines of a certain type of airplane are mounted in such a way that their thrust is not directed parallel to the airplane's plane of symmetry, but forms a certain angle of decalage ξ with it, the above considerations must be supplemented by taking this angle into account. It is easily shown that its influence /89 will be dual: firstly, it will change the arm at which the unbalanced thrust acts, and, secondly, there will be a direct effect of the transverse component of running-engine thrust on the airplane's lateral motion.

As we see from Figs. 47 and 48, both of these factors act in the same direction (positive with the engines toed in) when the engines are mounted forward of the airplane's center of gravity and will oppose one another when the engines are aft of the center of gravity. Incidentally, the influence of the angle of decalage is minor for the latter configuration as compared with such an important positive factor as the short arm of action of the unbalanced thrust inherent to this configuration (owing to the positioning of the engines right alongside the fuselage tail section).

In either case, slip in the direction of the failed engine is inevitable in unbalanced-thrust flight without roll. In analysis of the unsteady divergent motion that occurred immediately after lateral-engine failure, it was established that slip then occurred in the direction of the running engine. But in this case – that of steady unbalanced-thrust flight without roll – we see that the opposite picture materializes. Accordingly, even the aileron deflection required for such flight differs in magnitude and sometimes even in sign from that necessary to counter the roll at the very instant of engine failure. Actually, the bank in the direction of the failed engine was due to the action of the transverse static stability moment $M_x^\beta \beta$ and, for propeller-driven aircraft, /90 also by the action of the unbalanced wing wash moment $M_{x\ \mathrm{wash}}$, which has the same direction (toward the failed engine). In addition, the rotary-derivative moments ($M_x^{\omega_x} \omega_x$ and $M_x^{\omega_y} \omega_y$) came into play in the presence of the angular velocities of the lateral divergent motion.

In steady flight, these last two moments are naturally absent owing to the fact that $\omega_x = \omega_y = 0$. The unbalanced-wash moment may be diminished somewhat after feathering of the propeller on the failed engine — as before, the propeller produces no wash, but it at least no longer shades the washed part of the wing surface. On the other hand, the transverse-stability moment changes sign, acting against the slip in the direction of the running engines. Hence the magnitude and direction of the aileron deflection are determined in this case by the ratio of the opposed moments $M_x^{\beta}\beta$ and $M_{x\ \mathrm{wash}}$.

The ailerons of propellerless aircraft in steady unbanked flight with unbalanced thrust are almost always deflected toward the failed engine.

The rather large rudder deflection, together with the unbalanced wash over the fuselage, vertical tailplane, engine nacelles, and other parts of the airplane that are inevitable in the case in point result in an increase in aerodynamic drag. As a result, the already limited thrust margin that remains after failure of some of the engines on the airplane is further reduced. However, both the aerodynamic-drag increase and large required rudder deflection angles can be avoided by abandoning the unbanked flight that is customary and natural to the pilot in favor of another possible flight condition with unbalanced thrust: with a roll in the direction of the running engines.

5. ROLLING FLIGHT WITHOUT SLIP. REQUIRED ROLL ANGLE

A lateral component $G \sin\gamma$ of the force of gravity, directed spanwise along the body axis z and applied to the airplane's center of gravity, arises in unbalanced-thrust flight with a small roll in the direction of the running engines, as shown in Figs. 49 and 50. If the roll angle is so adjusted that the absolute magnitude of this component equals the lateral aerodynamic force arising from the rudder deflection, the factors giving rise to a lateral velocity component and hence to slip will be absent. Indeed, as is shown in Figs. 49 and 50, although the airplane flies banked in this case, there is no slip. Here the required rudder deflection angle and, consequently, the magnitude of the force Z_r will be /91
smaller than in the preceding case, because this force will have to generate the moment necessary to counter only the unbalanced-thrust moment, with no increments due to the moment of the lateral aerodynamic force Z.

Calculations indicate that roll is a more efficient way of generating a lateral force than slip. If, for example, the lateral weight component $G \sin\gamma$ necessary to balance the force Z_r is attained at a roll angle $\gamma = 3°–5°$, the lateral aerodynamic force Z of the same magnitude requires a slip angle $\beta = 6°–8°$ on a conventionally configurated airplane in unbanked flight.

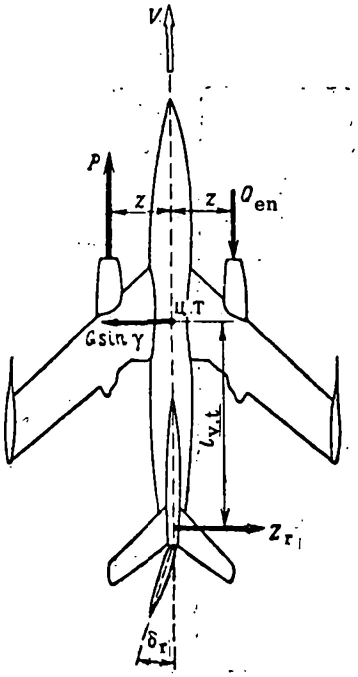

Figure 49. Zero-Slip ($\beta = 0$) Unbalanced-Thrust Flight with a Roll Angle ($\gamma \neq 0$).

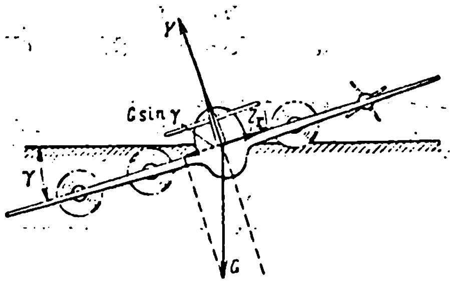

Figure 50. Compensation of Lateral Aerodynamic Rudder Force Z_r by the Lateral Component $G \sin \gamma$ of the Force of Gravity in Rolling Unbalanced-Thrust Flight.

The size of the roll angle needed for unbalanced-thrust flight without slip can be determined as follows. As we have shown, directional equilibrium of the airplane is ensured in this case by equilibrium between the unbalanced-thrust and deflected-rudder moments, i.e.,

$$(P + Q_{en})z = Z_r l_{v.t}.$$

But, as we see from Fig. 50, equilibrium of the lateral forces acting on the airplane requires observance of the equality

$$Z_r = G \sin \gamma.$$

Substituting the value of Z_r into the first of these formulas, /92 we obtain

$$(P + Q_{en})z = G \sin \gamma l_{v.t},$$

whence

$$\sin \gamma = \frac{P + Q_{en}}{G} \frac{z}{l_{v.t}}. \quad (7)$$

TABLE 3. VALUES OF THE ROLL ANGLES γ REQUIRED FOR NONSLIPPING UNBALANCED-THRUST FLIGHT

No.	Type of Airplane	Number of Nonrunning Engines	Nonrunning Engine Propeller Setting	Roll Angle deg
1	Tu-104, Tu-124, Tu-134	One	——	1.0
2	Il-18, An-10	One inboard	Feathered	0.5
3	Same	Same	Windmilling	1.5
4	"	One outboard	Feathered	1.0
5	"	Same	Windmilling	2.5
6	"	Two on same side	Feathered	2.5
7	"	Same	Windmilling	6
8	An-24	One	Feathered	2.0

Notes. 1. In all cases, the calculation was made for cruising speed and an average in-flight weight (full payload and 50% of normal fuel reserve).

2. The running engines are assumed to be working at the same settings, which support partial-thrust flight at cruising speed.

3. The required roll angle values obtained have been rounded off to the nearest half degree.

4. Level flight is, as a rule, inpossible for the case of line 7, and the roll angle given corresponds to flight without slip, but with loss of altitude.

This simple formula can be used to calculate the roll angle required for nonslipping unbalanced-thrust flight.

As the calculations show, this angle is quite small, ranging from 0.5 to 3°, for most present-day aircraft in realistic unbalanced-thrust flight modes. Table 3 gives the roll-angle values for unbalanced-thrust cruising flight of several passenger aircraft.

There is one misconception that sometimes appears in analyses of the influence of roll on the aerodynamic forces of an airplane in unbalanced-thrust flight. It reduces essentially to the idea that since the vertical component of lift (that directed along the line of action of gravity) is equal to Y cos γ, it will be /93 somewhat smaller in banked flight than in unbanked flight, and the pilot must have to increase the angles of attack slightly in order to ensure equality of the absolute values of lift and the weight of the airplane, which is necessary to maintain level flight. This, in turn, results in a corresponding increase in the aerodynamic drag that will hardly be smaller than that which has been avoided by eliminating slip in favor of roll.

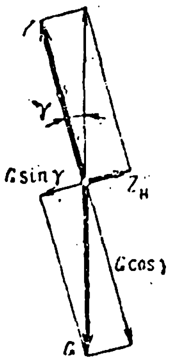

Figure 51. Equilibrium of Lift Y, Weight G, and Lateral Rudder Aerodynamic Force Z_r in Banked Unbalanced-Thrust Flight without Slip: $Y/\cos\gamma = Z_r/\sin\gamma = G$.

It is easily shown that these considerations are in fact in error. As we see from Fig. 50, the weight of the airplane is offset in this case not only by lift, but also by a component of the lateral aerodynamic force of the deflected rudder. In other words, equilibrium is ensured by the force triangle Y-G-Z_r (Fig. 51). The larger the roll angle, the greater the fraction of the weight taken by the force Z_r and, accordingly, the smaller the fraction taken by wing lift. In banked flight, the latter offsets only the weight component in the airplane's plane of symmetry. Hence the amount of lift required in straight-line banked flight is smaller than in unbanked flight and equal to $G(1-\cos\gamma)$. To develop this force, it is necessary to reduce the angle of attack accordingly. Consequently, the aerodynamic drag will also be smaller in banked flight with a roll corresponding to the condition $G \sin\gamma = Z_r$ than in any other case of unbalanced-thrust flight.

The above is compounded by the fact that for certain aircraft configurations, e.g., in low-wing designs, the lift is found to be smaller in the presence of slip than in the symmetrical-wash case at the same angle of attack.

Thus, zero-slip unbalanced-thrust flight with a roll angle has certain advantages over the case analyzed previously – that of flight without roll but with slip – as regards both the additional aerodynamic drag that develops (and hence more economical utilization of the remaining power margin) and the required amount of rudder deflection.

6. FLIGHT WITH SLIP AND ROLL TOWARD THE RUNNING ENGINES. REQUIRED RUDDER DEFLECTION. COMPARISON OF VARIOUS UNBALANCED-THRUST-FLIGHT PROCEDURES /94

In certain cases, interest attaches to one more possible technique for straight-line unbalanced-thrust flight – that with roll and slip in the direction of the running engines. Figure 52 illustrates the basic parameters of such flight. We see that since there is a slip angle in this case, the lateral aerodynamic force Z again inevitably makes its appearance. Now, however, this force is directed not toward the running engines, but toward the out engine. Consequently, the moment that it sets up in the yaw plane about the airplane's center of gravity acts not in the direction of the unbalanced-thrust moment, but in the opposite direction – the direction in which the deflected-rudder moment acts.

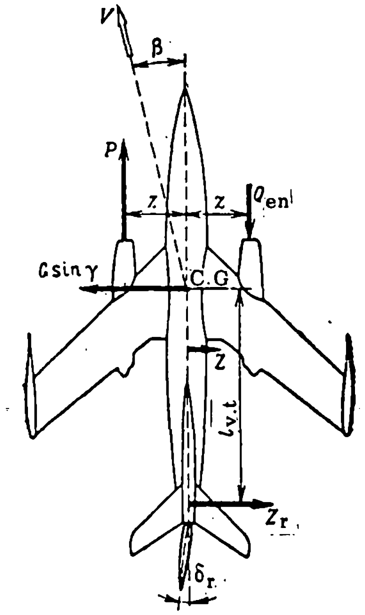

Figure 52. Unbalanced-Thrust Flight with Roll ($\gamma \neq 0$) and Slip ($\beta \neq 0$) Toward the Running Engines.

In other words, the lateral aerodynamic force does not tend to increase the unbalanced-thrust moment in this case, but helps counter it and is therefore transformed from an "enemy" to a "friend" of the rudder. As a result, the required rudder deflection angle is found to be even smaller than in banked flight without slip.

It should be noted that the amount of rudder deflection in steady unbalanced-thrust flight is not as important from the standpoint of pilot effort at the pedals as it was in the case of countering the divergent motion at the instant of engine failure, since this effort can almost always be relieved by use of the rudder trim tab or another mechanism with the same function.

Independently of the above, however, the required rudder deflection angle is of independent interest for two reasons. Firstly, deflection of the rudder tends to increase the airplane's aerodynamic drag and, secondly, separation of the flow past the rudder is possible at very large deflection angles, and this, in turn, /95 sharply lowers the effectiveness of the vertical tailplane and may, in some cases, lead to vibration – separation-induced shaking of the buffeting type. Finally, the required rudder deflection angle may, in certain cases of flight, simply be larger than the maximum possible (one such case will be analyzed below, in Chapter IV).

It is desirable in light of the above factors to find reliable methods of reducing the required rudder deflection angle in unbalanced-thrust flight. Among these methods, flight with roll and slip in the direction of the running engines is most reliable

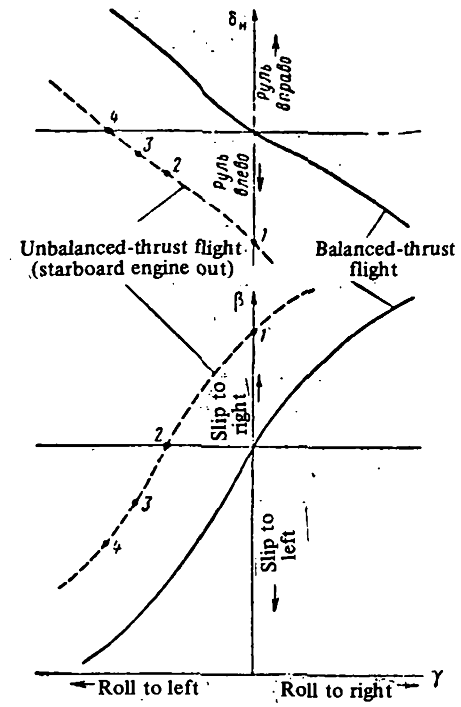

Figure 53. Required Rudder Deflection Angle δ_r and Slip Angle β as Functions of Roll Angle γ in Flight with Balanced and Unbalanced Thrust. 1) Slipping flight without roll; 2) rolling flight without slip; 3) flight with roll and slip; 4) flight with roll and with slip in neutral position of rudder.

and easiest of execution. For example, this technique makes it possible to ensure directional balancing of the airplane in straight-line flight at low speeds, when rudder effectiveness is down sharply and the balance between the disturbing ($M_{u.t}$) and restoring moments changes for the worse.

Figure 53 shows the required rudder deflection and slip angle as functions of roll in flight with balanced and unbalanced thrust. The solid lines correspond here to thrust symmetry, and the dashed lines to the unbalanced case.

Points 1, 2, and 3, which correspond to the three characteristic cases of steady unbalanced-thrust flight analyzed above, are marked on the latter.

If the roll continues to increase in the direction of the running engines, the required rudder deflection will become even smaller. And, finally, at a certain roll angle, the airplane will be able to fly with unbalanced thrust in a /96
straight line with the rudder in its neutral position (point 4). At some still larger roll angle toward the running engines, it would be necessary to deflect the rudder toward the failed engine instead of the running ones in order to hold to a straight-line course. However, such regimes are of no practical importance, being unfavorable from all points of view.

The possible piloting techniques for an aircraft in steady flight with unbalanced thrust differ superficially from one another only by a few degrees of roll. Looking at the airplane from the side, it would almost impossible to determine which of these piloting techniques had been chosen by the pilot. However, these few degrees are extremely important, since they result in substantial differences in the handling of the airplane and even its performance data.

By way of illustration, we cite the example of the heavy four-engined An-22, for which a one-degree roll-angle change results in a 25-30-kgf change in required pedal effort in straight-line unbalanced-thrust flight.

We can therefore formulate the basic advantages and disadvantages of the various methods of handling an airplane in straight-line flight with unbalanced thrust.

1. From the standpoint of obtaining the lowest possible aerodynamic drag and, consequently, the smallest sacrifice of aircraft performance, the flight regime with roll but without slip is the optimum. Deviations from this condition, especially in the direction of smaller roll angles, give rise to a drag increment and a loss of performance that are sometimes of decisive importance in spite of their small absolute magnitude (for example, when there is a question of the possibility of maintaining the required altitude, not to mention the very possibility of continuing flight).

2. The amount of rudder deflection necessary to fly in a straight line diminishes with increasing roll angle toward the running engines.

3. The most natural pilot posture, or at least the most familiar one, and, as will be shown below, the most natural instrument readings are obtained in unbanked flight with the slip that inevitably arises in this case.

The question as to which piloting technique should be regarded as the optimum in unbalanced-thrust flight has been discussed on more than one occasion in the specialized literature. Different authors have voiced preference for different techniques, attaching varying degrees of importance to the advantages and disadvantages of each technique as stated here. Thus, the present author has repeatedly spoken out in favor of banked flight without slip. Other investigators, while recognizing the advantages /97 of this technique, still feel that it "requires a great deal of skill from the pilot" [2]. Another argument that has been advanced — though only in reference to the Il-14 airplane — is that "this method, though acceptable, is more complicated than flying with zero roll and a small amount of slip. In instrument flying in clouds, maintaining speed by artificial horizon in banked flight requires additional pilot attention" [11]. We should note that this last argument is disputable. As was shown above, the required roll angle for nonslipping flight is so small that it can hardly interfere with normal perception and correct evaluation of the artificial-horizon readings, especially in pitch. In addition, the amount of slip in zero-roll flight with unbalanced thrust does not depend on the will of the pilot, and there is no guarantee that it will be possible to get by with "a small amount of slip" in all cases of flight if this piloting technique is used.

Thus, while there is a certain amount of disagreement on this question, we are inclined to the view that they are only apparent. It is evidently impossible to arrive at a single piloting technique that will be the universal optimum in all possible cases of unbalanced-thrust flight. It would be to our advantage to choose a flight regime for the particular airplane under the particular conditions, using as a basis the critical factor among those enumerated above.

Thus, if the engines are so positioned on an airplane that the unbalanced-thrust moment set up by failure of one of them is relatively small, if the power margin fully supports level flight at the necessary altitude with adequate speed, if the rudder is effective enough, and if the pedal effort is fully relieved with the trimmer, then unbanked flight is acceptable, and the comfortable customary pilot posture and instrument readings can be preserved. This applies, in particular, to such aircraft as the Tu-104, Tu-124, and Tu-134, as well as to the Il-18 and Il-62 with inboard-engine failure, to the British de Havilland "Comet," and certain others.

If, however, the airplane's power margin is small and it is difficult to maintain level flight with partial thrust at the given altitude, it is more expedient to fly with a roll angle and no slip.

Finally, if the rudder-effectiveness margin is the critical element, as was the case, for example, on certain types of aircraft when they were throttled forward during landing approaches with unbalanced thrust, it is best to use larger roll angles that cause slip toward the running engines and thereby provide an increase in rudder-deflection margin.

Other factors may assume a similarly decisive role for the same airplane in different stages of a flight and at different altitudes. Thus it is by no means always possible, even for a given type of airplane, to give a single recommendation for piloting with unbalanced thrust. For example, in the case of the same Il-14 airplane, both the power margin and the rudder-deflection margin permitted zero-roll flight without having to deal with slip in cruising flight at moderate altitude with the propeller of the out engine feathered. However, on an engine failure during a climb at low speed (immediately after takeoff), when the running engine is already operating at maximum power and, consequently, generating its maximum unbalanced-thrust moment, rudder-deflection margin emerges as the critical factor. If flight is continued with no roll angle, the rudder margin may be inadequate to keep the machine from yawing. Consequently, the correct recommendation, which is found, for example, in A.I. Okhonskiy's paper [11], is to roll the airplane 5°-6° in the opposite direction at the instant of engine failure and by 1°-2° during the steady climb that follows. /98

Even on an airplane like the Tu-104, for which the thrust inbalance that arises on failure of one of its engines is comparatively small and it is unnecessary to bank in the direction of the running engine at most stages in a flight, 3-4° of roll on an engine failure immediately after takeoff increases the rate of climb by more than one m/sec as compared to zero-roll flight — thus facilitating clearance of obstacles and helping the pilot reach a safe altitude sooner.

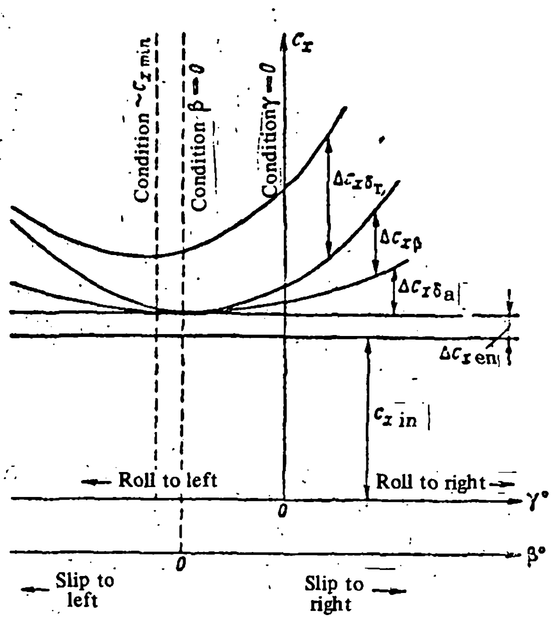

Figure 54. Variations of Aerodynamic Drag Coefficient and Its Components for an Airplane in Flight with Unbalanced Thrust at Various Angles of Roll γ and Slip β.

In writing recommendations for the handling of each specific type of aircraft, it is necessary to give instructions for controlling the aircraft in unbalanced-thrust flight with specific identification of the flight conditions (altitude, speed, number and locations of out engines, propeller-blade settings for these engines, etc.) in which flight may be continued at zero roll and to specify regimes in which a bank is necessary to ensure zero-slip flight and those in which it is necessary to bank the aircraft to produce slip in the direction of the running engines.

The changes in the airplane's total aerodynamic drag coefficient and those of five of its basic components in unbalanced-thrust flight with various angles of roll and slip are shown schematically in Fig. 54.

The first, the initial drag $c_{x\ in}$, corresponds to normal balanced-thrust flight.

The second component is the drag increment of the out engine, $\Delta c_{x\ en}$. The figure indicates that this component is relatively small. And when we are concerned with the aerodynamic drag of a nonrunning turbojet or turbofan engine, or even that of a turbo- /99
prop engine whose propeller has been feathered, this quantity is indeed comparatively small. However, it must be recalled once again that if for some reason the propeller of a failed engine on a turboprop airplane has not been feathered, the drag increment that it generates will be very large (commensurate with

the initial aerodynamic drag of the entire airplane).

The third component is the increment $\Delta c_{x\ \delta_a}$ due to the additional aileron deflection, which, in turn, arises from the need to counter two types of transverse moments that arise in unbalanced-thrust flight:

a) the moment of lift imbalance that appears on propeller-driven aircraft owing to the removal of wing wash in the zone of the out engine;

b) the transverse stability moment.

The first of these quantities is practically independent of the angle of roll, while the latter is functionally related to this angle via the angle of slip.

The fourth component is the drag increment due to slip (crosswash), $\Delta c_{x\ \beta}$.

The fifth component is the drag increment $\Delta c_{x\ \delta_r}$ from the deflected rudder. This component naturally depends on the rudder deflection angle necessary for flight at the particular angle of roll.

We see from Fig. 54 that the regime corresponding to minimum /100 aerodynamic drag and that corresponding to zero slip resemble one another quite closely. Strictly speaking, however, the angle of roll at which the former is attained is somewhat larger than for the latter. The reason is that although the fraction of drag due to crosswash (slip) reappears and begins to increase when the angle of roll is increased beyond $\gamma_{\beta=0}$, there is at the same time a continued decrease in the fraction of drag due to the rudder deflection. In a certain very narrow range of angles of roll, the decrease in $\Delta c_{x\ \delta_r}$ is found to be more effective than $\Delta c_{x\beta}$. This is also why the $c_{x\ \min}$ regime is shifted with respect to the $\beta = 0$ regime. However, this shift is so small that these two regimes may be regarded as practically identical, and either can be resorted to in any case in which the airplane's performance data (vertical velocity, level-speed range, etc.) are at their limits.

Needless to say, the performance gain attained by zero-slip nonrolling flight is very modest in absolute magnitude. But if the question is one of the very possibility or impossibility of continuing flight or one of entering or avoiding the dangerous-altitude zone, then even an extra 0.3-0.5 m/sec of climbing rate or an extra 10-15 km/h of speed range may be decisive.

To illustrate this last point, we might cite certain two-engined aircraft of the Second World War for which opinions differed as to their capacities for one-engine-out level flight. The Pe-2 and Il-4 were examples of such aircraft.* Needless to say, other factors of an objective nature may also have been in operation, such as individual differences between engines and aircraft and ambient-air-temperature differences in particular. In colder air, the engine that kept running would, all other conditions the same, develop a higher power output. In addition, the louvers of its cooling system could be closed down farther than in flight in warmer air. As a result, the same airplane could fly on one engine in winter, but not in summer. However, all conditions equal, including equal air temperatures, some pilots could fly these air- /101
craft with one engine out and some could not. There is no doubt that the basic reason for these differences should be sought in the ability to utilize modest resources – primarily by applying a procedure as simple but effective as rolling in the direction of the running engine. These few degrees of roll frequently decided the question as to whether flight could or could not be continued.

In many cases, utilization of these small reserves makes it possible to gain several hundred meters of ceiling altitude with the powerplant in partial operation, and this, in turn, makes it possible to avoid entry into a zone of congested cumulus clouds, high turbulence, or other dangerous phenomena, especially if the airplane is flying in a vertical-separation scheme. In this case, the gain of these few hundred meters may mean gaining a whole interval between two levels of like direction, which, for example, amounts to 2 km at the operating altitudes of modern aircraft ($H \geq 9$ km) (Fig. 55).

7. INDICATION OF SLIP IN FLIGHT WITH BALANCED AND UNBALANCED THRUST

As we have shown, the sign and magnitude of the slip strongly influence the characteristics of steady flight with partial and unbalanced thrust. The question naturally arises as to the indi- /102
cation of this extremely important parameter of the airplane's motion. It is customary to assume that the existence and direction of slip can always be judged by reference to an instrument designed specifically for this purpose – the slip indicator included among the pilot's equipment of every airplane, usually in unit with a turn indicator or artificial horizon (Fig. 56).

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*It is difficult to give examples of aircraft of more modern design because all presently existing two- and multiengined aircraft are distinctly capable of prolonged level flight with fewer than all of their engines in operation.

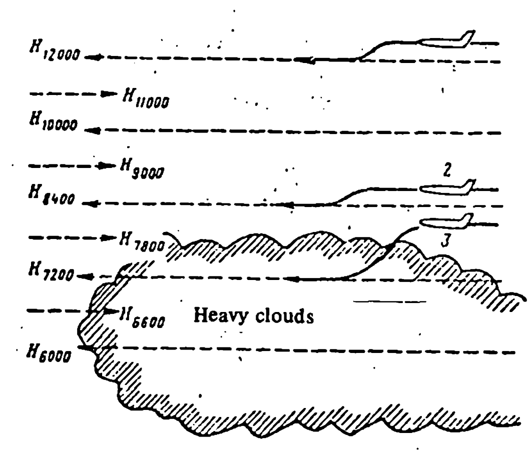
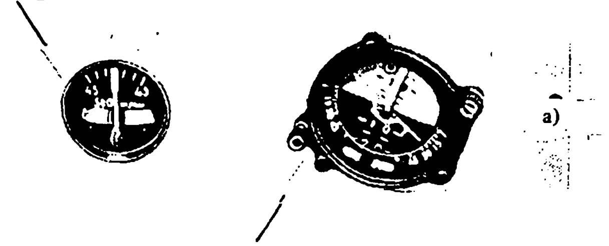


Figure 55. Diagram of Level Assignment in Motion of Airplane. 1) Ceiling of airplane in flight with full thrust (optional level H_{12000}); 2) ceiling of airplane in flight with unbalanced thrust, $\beta = 0$, $\gamma \neq 0$ (optional level H_{8400}); 3) ceiling of airplane in flight with unbalanced thrust, $\gamma = 0$, $\beta \neq 0$ (descent to level H_{7200} is mandatory).

Slip indicator combined with turn indicator. Straight-line flight with slight bank to the right.



Slip indicator built into artificial horizon. Coordinated turn to the right.

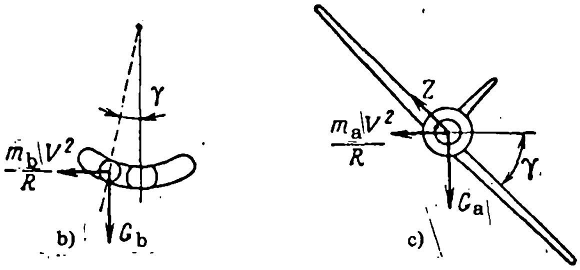


Figure 56. Slip Indicators (a) and Diagrams of Forces Acting in the Transverse Plane on the Slip-Indicator Ball (b) and on the Airplane as a Whole (c).

The slip indicator is an arc of tubing in which a metal ball is allowed to shift back and forth freely. The tube is filled with a special fluid to damp small random oscillations of the ball.

In straight-line zero-roll flight, the ball assumes a central position in the tube. This position is usually bracketed by special marks that form the so-called "pocket." It is assumed that when the ball is in the "pocket" there is no slip and, conversely, that the ball can leave this position only in the presence of slip. In reality, however, the position of the ball depends not on slip, but only on the lateral load factor n_z acting on the airplane, which is not related to slip in the general case. As a result, the slip-indicator readings are not reliable in all /103 flight cases. Thus, as we have said, slip is inevitable in steady-state unbalanced-thrust flight with zero roll, but the indiator ball remains in its central position, i.e., it gives no slip indication.

To understand the causes of this phenomenon and to put precise limits on the list of flight cases in which the slip-indicator readings are unreliable, it is necessary to consider the relations to which the operation of this instrument is subject.

The motion of the slip-indicator ball and the motion of the airplane as a whole along its transverse axis z are determined by the respective equations

$$\left.\begin{aligned} G_b \sin\gamma + \frac{G_b V^2}{gR}\cos\gamma = 0; \\ G_a \sin\gamma + \frac{G_a V^2}{gR}\cos\gamma + Z = 0, \end{aligned}\right\} \qquad (8)$$

where the subscript a applies to the airplane and b applies to the instrument ball.

As we see on comparing these equations, the lateral displacements of the airplane and the ball are subject to the identical laws in the absence of an unbalanced transverse aerodynamic force Z (or one that is balanced by forces of nonaerodynamic nature), so that a deflection of the ball from the plane of symmetry is a reliable signal indicating slip. This situation obtains in flight with symmetrical thrust. However, in the presence of a force Z, as is typical of unbalanced-thrust flight, the identity of the above two equations is violated, with the result that the relation between slip and indicator-ball deflection from neutral also breaks down (see Fig. 56).

The position of the slip-indicator ball is determined only by gravity and the inertial forces applying to it. No other forces, and no aerodynamic forces in particular, act directly on the ball. In the aforementioned case of unbalanced-thrust, zero-roll flight, the transverse component of the ball's weight, which could deflect it from its central position, is absent because there is no roll, and inertial forces are absent because the airplane is flying in a straight line, i.e., without lateral accelerations. As a result, there is no cause for the ball to leave its central position.

Conversely, if an airplane is flying with unbalanced thrust and no slip, but with a roll, then despite the absence of slip, the ball will leave its central position in the direction to which the airplane is banked, since it will be acted upon by the totally uncompensated transverse component of its weight. Again in this case, therefore, the slip-indicator readings will not reflect /104
reality.

It must be stressed that all of the above applies only to steady flight, i.e., flight without rotation around the vertical axis. But in the first instant of divergent motion following failure of one engine, the ball deflects on inertia; as soon as straight-line flight is restored, however, it returns to a position determined only by the presence or absence of a bank.

The presence of an uncompensated lateral aerodynamic force component is a convenient criterion for the reliability of slip-indicator readings. In fact, as we have shown, the motion of the airplane as a whole along the z axis in symmetrical-thrust flight is subject to the same relations as the motion of the ball, and if the latter has left its central position, it has done so only as a result of action of the Z component on the airplane (but not on the indicator ball). This component may be either totally uncompensated or compensated by a force of different, nonaerodynamic nature. In either of these two cases, however, the slip-indicator ball will be deflected from its central position under the action of inertia or gravity, respectively. In practical flying, this situation generally arises in slip. Therefore the pilot's habit of judging the presence and direction of slip from the slip-indicator ball is fully justified.

The case of slipping flight with unbalanced thrust and zero roll is one of the exceptions. Here, lateral equilibrium of the forces acting on the airplane in its transverse plane is attained through the interaction of only the aerodynamic forces: $Z_r = Z$. Consequently, the resultant lateral component of the aerodynamic forces is zero and the ball remains centered despite the slip.

The case of zero-slip banking flight with unsymmetrical thrust is also an exception from the general rule; in it, the lateral aerodynamic force Z_r is compensated by the nonaerodynamic lateral component of the airplane's weight $G \sin \gamma$, and the ball is deflected even though there is no slip.

Thus, a general proposition can be stated: the slip-indicator ball is deflected from its central position when the airplane is acted upon by a lateral aerodynamic-force component.

In balanced-thrust flight, this is possible only in the presence of slip; hence the action of a slip indicator based on this principle.

In unbalanced-thrust flight, the relation between the operation of the transverse aerodynamic force and the presence of slip breaks down and, consequently, the slip-indicator readings become unreliable. /105

We should add that everything said above concerning the slip indicator and the action of various forces on it in flight also applies to the human body, which is acted upon, like the entire airplane, by the forces of gravity and inertia but, unlike the airplane, is not acted upon directly by aerodynamic forces. Hence the subjective perceptions of the pilot in unbalanced-thrust flight are just as deceptive as the slip-indicator readings.

In steady zero-roll flight with slip, the pilot will not physically sense this slip, and conversely, in flight without slip but with roll, the pilot's body will sense the action of the lateral component of its own weight. This last fact would appear to explain the diffident attitude of some pilots toward the above analysis of the parameters of unbalanced-thrust flight, the results of which indeed do not reconcile at once with either the subjective perceptions of the pilot or the readings of such a common and, it would appear, reliable piloting instument as the slip indicator.

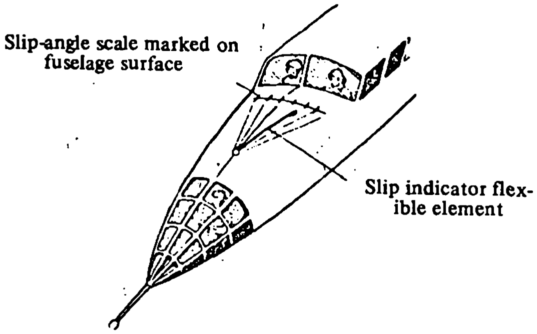

Slip-angle scale marked on fuselage surface
Slip indicator flexible element

Figure 57. Diagram Illustrating Action of Flexible-Element Slip Indicator in Outside Airstream.

We may conclude from the above that some other device whose operation is based on principles that do not become invalid in unbalanced-thrust flight should be used to indicate slip in that case.

Of such principles, the most dependable and natural is direct determination of the direction of the oncoming airstream with the aid of weathercock- or flexible-element devices (Fig. 57). Apart from their extreme simplicity and consequent high reliability, the advantages of such devices also include the fact that they permit /106 not only establishment of the very fact of slip and its direction, but also measurement of the slip angle. In many cases, this last fact may be extremely helpful, for example, if a certain maximum slip angle that may not be exceeded in normal operation has been established for the particular type of aircraft.

The disadvantages of indicators of this type include the fact that they indicate the direction not of the free stream, but of the stream flowing past the aircraft at the mounting point of the weathercock or flexible element. This makes it necessary to calibrate them and space the markers on their scales accordingly.

One might suggest the development of yet another type of indicator that would be useful in unbalanced-thrust flight, namely: special indication of the roll angle required for zero-slip flight (unless, of course, the slip angle is indicated directly). However, such devices have not as yet come into practical use.

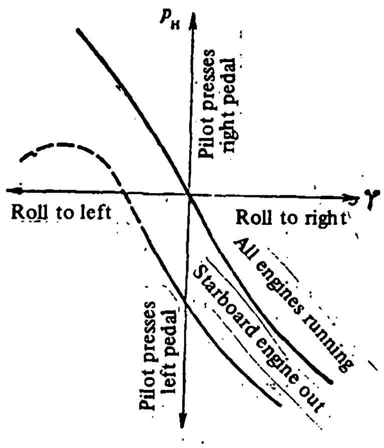


Figure 58. Rudder-Pedal Effort P_r as a Function of Roll Angle γ in Straight-Line Flight with Balanced and Unbalanced Thrust.

After the unbalanced-thrust flight regime has been stabilized and the rudder has been set to its final position, the pilot usually uses the trim tab to cancel the effort necessary to hold it in this position. Subsequent variations of this effort can also be used as a means of monitoring maintenance of the roll angle required for the selected flight regime. On most modern aircraft, a minute change in this angle usually generates appreciable rudder forces (if, of course, the pilot is holding the airplane in straight-line flight). A 1°-2° change in roll angle increases the rudder-pedal effort by tens of kilograms. This is the case in flight with both balanced and unbalanced thrust (Fig. 58) and can be used as a secondary criterion of steadiness of flight.

Such an additional criterion becomes necessary, for example, under the conditions of instrument (blind) flying, when holding the aircraft at the small roll angle necessary for zero-slip unbalanced-thrust flight (1°-3°) with the /107 necessary accuracy is made very difficult by the inaccuracy of the artificial-horizon readings in this angle range.

Once the roll necessary for zero-slip unbalanced-thrust flight has been established, therefore, it is advisable to maintain it thereafter by reference not only to the visible natural horizon or the artificial horizon, but also by the absence of changes in the pedal effort required to hold a constant heading. Actually, this criterion is used subconciously by pilots in ordinary straight-line balanced-thrust flight, with the difference that the amount of roll required is zero in this case, instead of the nonzero value in unbalanced-thrust flight.

8. NAVIGATION ELEMENTS OF UNBALANCED-THRUST FLIGHT

In unbanked unbalanced-thrust flight, the handling difficulties described above are compounded by certain peculiarities in the matter of aerial navigation.

Navigating difficulties encountered in unbalanced-thrust flight have been reported on more than one occasion by aerial navigators [17].

The familiar formula

$$CA = CC + \Delta_c + \Delta_m + AC,$$

which connects the compass course (CC) to the direction of flight, i.e., to the course angle (CA), acquires, in addition to the quantities determining the differences between the values of these angles (the compass deviation Δ_c', the magnetic declination Δ_m at the position of the aircraft, and the angle of crab AC due to the wind), one more term: the value of the angle of crab due to slip. It is possible to introduce the value of this angle into the navigator's calculations in order to correct them appropriately after transition from balanced-thrust to unbalanced-thrust flight only if the airplane has quantitative slip indicators. Otherwise, it is necessary to make an in-flight determination of the crabbing due to slip by ordinary navigating methods, i.e., in the same way as the wind drift is determined. In practice, the navigator may not even resolve the above two components, and perceive the slip crab as a corresponding change in the lateral wind component. However, it is necessary that the crew recognize beforehand that this arbitrary resultant quantity, which incorporates lateral drifts due to two fundamentally different factors, must change on possible subsequent changes in the degree of thrust imbalance, and sometimes even reverse its sign.

In performing aerial-navigation calculations for unbalanced-thrust zero-slip flight, it becomes necessary to apply corrections /108 to the readings of the conventional (not the distant-reading) magnetic compass owing to the errors that arise when its card is deflected out of the horizontal plane.

With such deflections, the compass readings are influenced by the vertical component of the earth's magnetic field. The errors that arise then are larger the larger the angle of roll and also the higher the latitude at which the airplane is flying, since the vertical component of the magnetic field increases with increasing latitude.

When a distant-reading compass is used, it becomes unnecessary to apply such corrections, since the inductive transducer on which the sensitive element of this type of compass is mounted is an electric gyroscope the vertical position of whose spin axis is automatically corrected. The sensitive element of the compass is suspended on the frame of the gyroscope and, in virtue of the gyroscope's action, keeps its plane horizontal irrespective of the aircraft's angle of roll.

9. MANEUVERING IN FLIGHT WITH PARTIAL AND UNBALANCED THRUST. TURNS IN THE DIRECTION OF THE RUNNING AND NONRUNNING ENGINES. VARIATION OF FORWARD FLIGHT SPEED. INFLUENCE OF THRUST IMBALANCE ON LONGITUDINAL STABILITY AND BALANCE

The execution of turns in flight with partial and unbalanced thrust has been treated differently in different investigations.

Some of the flight manuals presently in effect state that turns should be made in unbalanced-thrust flight only in the direction of the running engines in the interests of flight safety.

It appears that there was some justification for this view at earlier stages in the development of aviation, when aircraft had comparatively small power (thrust) margins and inadequate rudder-effectiveness margins. Moreover, the aircraft in use were predominantly propeller-driven types having their required-power minima at angles of attack near the economy value. In partial-thrust situations, therefore, such aircraft were usually flown at (or quite near to) precisely this angle of attack, which provided for retention of the small power margin that remained at the pilot's disposal in such cases. As we know, when the airplane was banked, the angle of attack of the dropped wing increased further (see Fig. 22).

For the above reasons, it was necessary to take care not to approach the separation range in banking toward the out engine. /109
And the lack of adequate rudder margins suggested that if the amount of rudder deflection was barely enough to counter the unbalanced-thrust moment in straight-line flight, it would not be enough to bring the airplane back into straight-line flight from a turn deliberately started toward the out engines (when it is necessary to overcome not only the unbalanced-thrust moment, but also rotational inertia).

In itself, however, observance of these recommendations as to the execution of turns toward the running engines generated certain additional difficulties in many cases. As a rule, the power margin of propeller-driven aircraft flying with partly inoperative powerplants was reduced so sharply as to prohibit continuation of level flight in many cases, and especially in the landing configuration. If, on the other hand, subsequent flight involved a forced descent, the time available to the pilot was

$$t=\frac{H}{V_y},$$

after which, in one way or another, the airplane had to be landed at an airport or at least on an area suitable for a forced landing.

The location of this area relative to the airplane often dictated a turn in a certain direction in order to reach the intended landing spot by the shortest and, consequently, fastest route (Fig. 59). These conditions gave rise to a paradoxical situation in which the turn in the direction of the running engines, which was recommended as being the safest, could result in a forced landing at a place totally inappropriate for the purpose. At the same time, a turn toward the out engines, which was regarded as risky, gave better chances of reaching the desired landing point.

Thus, in the face of the above considerations, experienced pilots sometimes resorted to turns toward the failed engines even with older types of aircraft when circumstances demanded it [21].

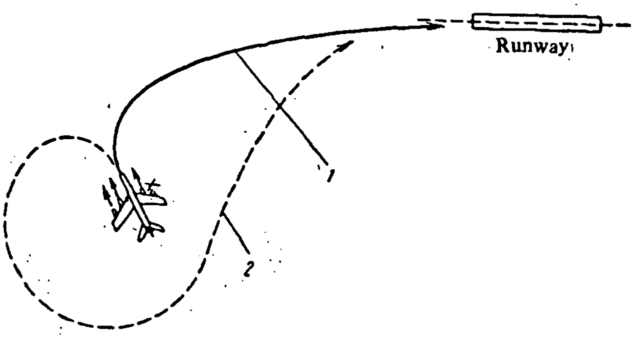


Figure 59. Paths of Landing Approach After Partial Powerplant Failure with Turns Toward the Running and Out Engines. 1) Landing approach with turn toward out engine; 2) landing approach with turn toward running engines.

Moreover, the considerations that once made it expedient to execute unbalanced-thrust turns only in the direction of the running engines have lost most of their force for modern aircraft. In fact, the thrust margins of modern aircraft with high thrust-weight ratios are such that even when 50% of the engines fail, their powerplants permit flight at a speed substantially above the safety speed. Further, even if it is necessary to make maximum use of the potential power output of the remaining running engines on a jet airplane, it should be flown not at the economy angle of attack, but /110 at the optimum angle, which is farther removed from the separation range. The rudder-deflection-angle margins of modern aircraft are also generally larger than on those of the recent past.

For these reasons, there is no longer any real basis for hesitating to execute unbalanced-thrust turns in either direction.

However, it must be stipulated that the turns must be coordinated to ensure full flight safety in such cases.

In essence, the advantages of coordinated turns as compared with uncoordinated turns prevail in flight with balanced as well as with unbalanced thrust. In the latter case, however, certain handling peculiarities arise owing to the fact that a certain amount of roll toward the running engine has already been necessary for straight-line nonslipping unbalanced-thrust flight. This naturally makes it necessary to reckon the angle of roll not from zero, but from the angle $\gamma_{u.t}$ already assumed in straight-line flight. In other words, a coordinated turn at a given angular velocity in unbalanced-thrust flight requires, all other conditions the same, a larger amount of roll if the turn is made toward the running engines and a smaller roll if it is made toward the out engines. Accordingly, the values of the maximum permissible angles of roll γ_{max} for aircraft of limited maneuverability

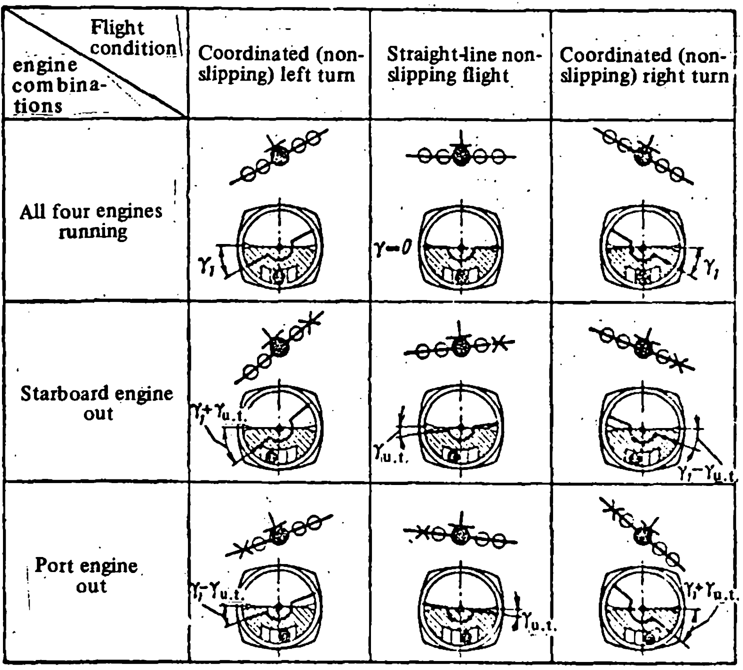


Figure 60. Spatial Position of Airplane and Instrument Readings During Turns with Balanced and Unbalanced Thrust. γ_1 is the roll in a normal coordinated turn with the powerplant fully operative; $\gamma_{u.t}$ is the roll in straight-line zero-slip flight with unbalanced thrust.

(e.g., passenger types) must also be shifted to $\gamma_{max} + \gamma_{u.t}$ in /111 turns toward the running engines and $\gamma_{max} - \gamma_{u.t}$ in turns toward the out engines.

Figure 60 shows schematically the readings of the artificial horizon, turn indicator, and slip indicator in balanced- and unbalanced-thrust flight without slip, including coordinated turns in both directions.

Experience has shown that some crew members are confused by the unaccustomed combination of instrument readings during turns toward a failed engine: the turn-indicator flag is deflected in the direction opposite to that of the ball deflection. Pilots know from practical flying with balanced thrust that this situation arises in a so-called "turn with too much foot," i.e., a turn in which the angular velocity of the rotation on the vertical axis is disproportionately large for the particular angle of roll and the particular speed, with the result that the airplane skids – a /112 phenomenon that is without question undesirable and in certain cases even dangerous.

However, this interpretation of the instrument readings is valid only for flight with balanced thrust. When thrust is unbalanced, a small deviation of the slip-indicator ball toward the running engine indicates, as we have shown, precisely that there is no slip. Consequently, the instrument readings shown in Fig. 60 for the case of a turn toward an out engine actually correspond to an accurate coordinated turn.

In unbalanced-thrust flight on a modern airplane, the pilot is free to choose the direction of a turn in each specific case as a function of the airplane's heading relative to the one that must be taken, the presence and location of obstacles (hills, congested cumulus or cumulonimbus clouds, etc.) relative to the initial heading, and even as a function of visibility to the left and right from the pilot's seat.

Naturally, the motion of the airplane in the longitudinal plane depends on thrust symmetry to a much lesser degree than does its lateral motion. Nevertheless, certain changes in longitudinal-stability behavior may be observed following failure of a lateral engine.

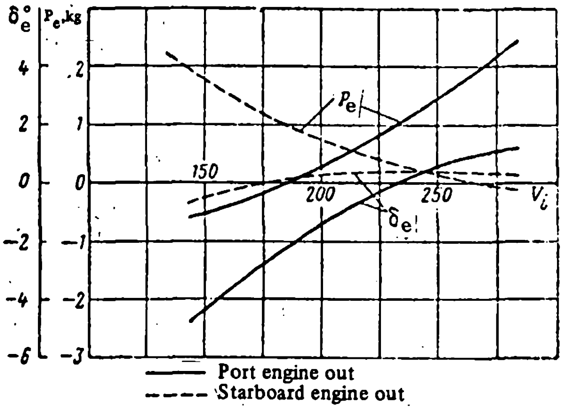


Figure 61. Longitudinal Stability Characteristics of a Two-Engined Airplane with Right-Hand-Rotating Propellers in Flight on One Engine ($\gamma = 0$).

As we know, the steady speed corresponding to a given elevator position or a given control-column effort depends on thrust. When one or two engines fail, therefore, this speed changes (toward the value that it has with the powerplant at idle). The slope of the airplane's trim curves* usually changes on going from full throttle to all-engines-idle. It changes to a much lesser degree, of course, when this transition is made not with all engines, but only by one or two that have failed.

On propeller-driven aircraft, failures of port and starboard engines sometimes affect longitudinal stability differently; this can be explained by the differences that occur in such cases in the downwash changes at the horizontal tailplane. Figure 61 presents longitudinal-stability characteristics obtained by A.L. Raykh, D.A. Sorkin, and V.G. Tabachnikov for cases of hands-off and locked-controls flight of a two-engined airplane with right-hand-rotating propellers in flight on the port and starboard engines.

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*The longitudinal-stability trim curves express the elevator deflection δ_e and the fore-and-aft effort P_e at the control column as functions of steady-state flight speed. These curves are used to draw inferences as to the sign (and approximate degree) of the airplane's longitudinal stability with the controls locked and when flown hands-off, respectively.

The maneuverability characteristics of an airplane also include its forward-speed curves. As we know, longitudinal positive and negative accelerations are determined by the respective formulas /113

$$\left.\begin{aligned} j_{\text{pos}} &= \left(\frac{P-Q}{G} - \sin\theta\right) g, \\ j_{\text{neg}} &= -\left(\frac{Q}{G} + \sin\theta\right) g. \end{aligned}\right\} \qquad (9)$$

We see from the above formulas that the available thrust margin (P - Q) – the basic parameter whose value changes substantially after a partial powerplant failure – appears only in the positive acceleration formula. Thus, as we should expect, positive accelerating capability drops off sharply as compared with full-thrust flight even within the reduced range of flight speeds that remains after partial engine failure. As a result, any pilot error involving a loss of true speed below the necessary level is corrected much more slowly than usual in partial-thrust flight. In all cases in which the altitude margin permits, it is advisable to help the airplane accelerate by giving up a small amount of this altitude. In flight at low altitude, when acceleration cannot be forced by descending further, it is necessary to watch speed especially closely, remembering the difficulty of making up a loss of speed without full powerplant thrust.

In most cases, deceleration of an airplane in flight after partial engine failure involves practically no differences from the same maneuver when carried out with the entire powerplant working. Actually, to slow down a properly functioning airplane, the pilot reduces engine thrust, i.e., he deliberately resets the engines to a speed similar to that which they would go to spontaneously in the event of failure. /114

However, in decelerating after a partial powerplant failure, it is necessary to be aware at all times of the above limitations on the accelerating characteristics of an airplane flying with partial thrust and to make certain that the drop in speed is terminated on time at the intended value.

Because of its extremely high rate, the deceleration that occurs in the case of combined failure of a turboprop engine with its propeller-feathering system requires particular attention.

This maneuver is not executed intentionally because of the unacceptable negative acceleration inherent to it. However, if such a combined failure occurs spontaneously, the pilot must gear his actions to the need to counter not only the divergent lateral motion, but also the sharp drop in speed.

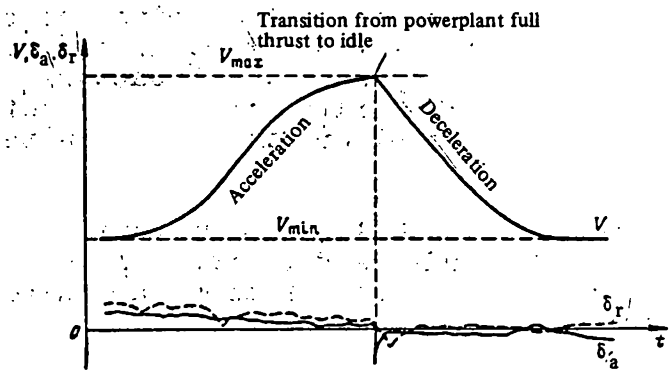

Figure 62. Changes in Aileron and Rudder Deflection Angles δ_a and δ_r in Straight-Line Acceleration and Deceleration.

Insignificant changes in the lateral balance of the airplane arise in normal flight with balanced thrust when the airplane is accelerated or slowed down (Fig. 62). These changes are caused by changes in the powerplant's reaction torques and gyroscopic moments with flight speed, and by the influence of small symmetry deviations in both the external shapes of the airplane and the rigidity characteristics of its wings, fuselage, and tail. In practice, the required rudder and aileron deflections during acceleration and deceleration are so small that they usually go unnoticed by the pilot unless he has been specifically instructed /115
to evaluate them.

In unbalanced-thrust flight, however, the situation changes substantially. To counter the unbalanced-thrust moment, it is necessary to deflect the rudder through a rather large angle. Rudder effectiveness changes with speed and, consequently, so does the angle through which it must be deflected.

With unassisted controls or controls that include a reversible rudder booster, this variation of the deflections does not usually produce any substantial changes in the effort that the pilot applies to the pedals. Why this is so becomes clear when it is recalled that both of the above quantities — rudder effectiveness and the effort required to deflect the rudder — are proportional to the square of speed.

On an airplane with irreversible rudder controls, the force required to deflect the rudder is determined entirely by the special automatic device. If the latter operates as a function of speed, i.e., if it changes the gradient $\partial P_r/\partial \delta_r$ in accordance with ram-pressure variations, the picture is generally the same as with the reversible booster or nonbooster controls.

On the other hand, if, as is often the case, the automatic rudder assist is a spring-type mechanism, the increase in the required rudder deflection as speed is brought down results in a corresponding increase in pedal effort. In this case, the pilot must be ready during deceleration to keep the airplane on a straight course at the cost of an effort that increases substantially as speed decreases.

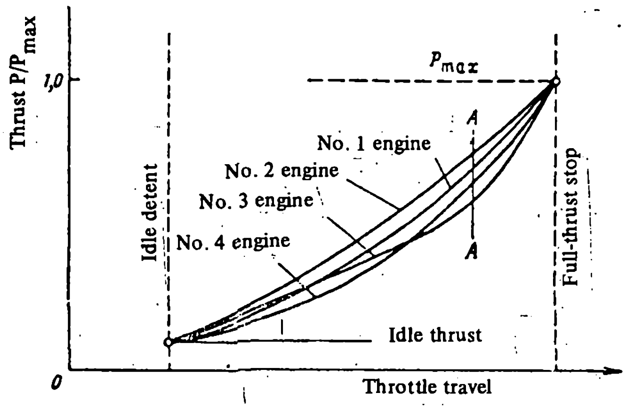

Figure 63. Thrust of Several Engines on the Same Airplane vs. Throttle Position.

When the throttles are moved to go from one flight regime to another, it is necessary to remember that the thrust outputs of all of the engines on the airplane change with a certain time lag after movement of the throttles and not in strict synchronism. This is because the engine-control system, especially on large multiengined aircraft, is strung out over tens of meters and incorporates many joints, bends, and other elements that inevitably set up elastic and mechanical play, and also because of the inevitable differences in tuning of the acceleration controls.

Kinematic adjustment of the control system of each engine reduces in practice to bringing the extreme positions (forward and back) of the throttle into correspondence with the necessary limiting engine-output modes (maximum and minimum). However, fixation of intermediate throttle positions having one-to-one correspondence to definite engine outputs is possible in practice /116
only with substantially lower accuracy.

Figure 63 presents a bundle of curves characterizing the thrust changes of four engines mounted on the same airplane as functions of throttle travel. It shows that even if the throttles are moved in strict synchronism from one position to another, there are, in the range of intermediate positions (e.g., in section A-A), inevitable differences in the thrusts obtained from the individual engines, i.e., in other words, despite the fact that the entire powerplant is in working order, the airplane develops a certain thrust imbalance. This imbalance may have an appreciable influence on the flight performance of aircraft with certain characteristics. In one case, when an experimental multiengined aircraft was making a landing approach, the pilot throttled forward, i.e., used a certain temporary increase in thrust, to adjust his estimate. All four throttles were pushed slightly forward in synchronism. The response of the airplane to this ordinary pilot action was totally unexpected: the machine banked so sharply that one wingtip grazed the ground, and it was righted and landed safely only thanks to vigorous and speedy intervention by both pilots. Subsequent analysis of the event indicated that its prime cause was a thrust imbalance resulting from nonsynchronous buildup of thrust when the throttles were moved forward. The manifestation of this imbalance was particularly acute in this case owing to the deficient directional stability and, most importantly, the excess transverse stability that were inherent to the first few aircraft of the type that were built.

There are, generally speaking, three possible ways of preventing such undesirable reactions of the aircraft to a change in powerplant output. The first is to develop special control systems for the engines of multiengined aircraft that ensure the necessary setting-change synchronism. However, this approach involves substantial difficulties, of both design nature, e.g., the development of devices to compensate the influence of deformations of the airplane in flight, and of operational nature, such as the work needed to set up the powerplant as a whole and each of its engines in particular. Hence the possibilities for development of such systems are to a certain extent limited. /117

A second and apparently more promising approach reduces to endowing the airplane with stability and controllability characteristics with which its sensitivity to thrust imbalance will not be so strongly pronounced. Foremost among such characteristics, as we noted above (see Chapter II), are the coefficients of static lateral stability m_x^β and m_y^β and the quantity κ, which characterizes the relation between the maximum angular velocities of the lateral and directional divergent motion of the airplane.

Returning to the aircraft cited by way of example, it should be noted that these characteristics were improved substantially in the production version by reducing the dihedral of the wing cantilever sections by 1°, with a simultaneous 45% increase in vertical-tailplane area. All aircraft of that type now in service have a moderate, and in any event quite acceptable, amount of sensitivity to thrust imbalance due to nonsynchronous operation of the engine-control systems.

The third way to solve this problem reduces to the use of special automatic devices – automatic pilots, yaw and roll dampers, etc., which are designed into modern aircraft to give them acceptable stability and controllability characteristics over the entire range of speeds and altitudes at which the particular aircraft type is to operate, and to support certain basically new properties of the aircraft (up to and including automatic-landing capability). The increasingly widespread use of such devices, which is characteristic for present-day aviation, has resulted, on the one hand, from the impossibility of providing acceptable stability and controllability characteristics in a modern aircraft by purely aerodynamic means and, on the other hand, from the increased reliability of automation elements in aeronautical control systems. It is now difficult to conceive of an airplane that could be piloted "manually" without numerous automatic control devices /118 operating in combination and in parallel with the pilot.

Besides helping solve general problems of aircraft stability and controllability improvement, the use of automatic control devices also helps reduce the sensitivity of the airplane to thrust imbalance. At the present stage in the development of aviation, it would appear expedient to use all three of the above trends and reasonable combinations thereof, with preferential development of the last-named — automation.

At the same time, flight personnel must consider the possible appearance of a lateral divergent motion as a response of the airplane to nonsynchronous operation of the individual engine-control systems and have some idea of the probable degree of this reaction. The pilot will then always be able to avoid the dangerous consequences of nonsynchronous engine-thrust changes by quickly correcting the possible lateral motions of the airplane on an increase or decrease in thrust by appropriate deflections of the rudder or by individual resetting of the individual throttle levers.

Chapter IV /119

LANDING APPROACH AND LANDING WITH PARTIAL AND UNBALANCED THRUST

1. SPEED RANGE AND VERTICAL VELOCITY IN FLIGHT WITH PARTIAL AND UNBALANCED THRUST WITH THE AIRPLANE IN ITS LANDING CONFIGURATION

The landing approach and the actual landing are critical stages in flight with partial and unbalanced thrust. It may seem at first glance that since the descent and especially the landing involve reduction of thrust, the failure of one or more engines should affect these stages of the flight to a lesser degree than in route flight or to a much lesser degree than during the divergent motion at the actual instant of failure. However, there have been a number of cases in practice in which the pilot dealt successfully with an unexpected engine failure, steadied the airplane with partial and unbalanced thrust, flew it hundreds and sometimes even thousands of kilometers further in this condition, reached his airport of destination in good shape, but was unable to cope with the landing approach and landing.

Attempts to explain such cases in terms of causes of purely psychological nature (the pilot's relief on seeing his airport and a resulting relaxation of attention) were unconvincing. A more thorough analysis showed that specific peculiarities that are absent (or manifest to a much lesser degree) during other stages of the flight are inherent to the landing approach and landing with unbalanced thrust.

The first of these objectively existing complications is that when the landing gear and flaps are lowered, the aerodynamic drag of the airplane increases sharply. As a result, the thrust of the operative engines, which was quite adequate to support level flight with the gear and flaps up, may be inadequate in some cases for flight with the gear down and the wing flaps in their landing position.

Figure 64 illustrates the characteristic changes in power margin, level-flight speed range, and available vertical velocity in various configurations of an airplane. As we see from the figure, lowering the gear and deflecting the flaps to the landing position sharply reduce the available power margin and, consequently, also the forward-speed range and vertical velocity. The effect of lowering the gear is physically not quite the same as that of lowering the wing flaps. /120

In itself, in contrast to lowering the gear, moving the wing flaps from their retracted position to their takeoff position has

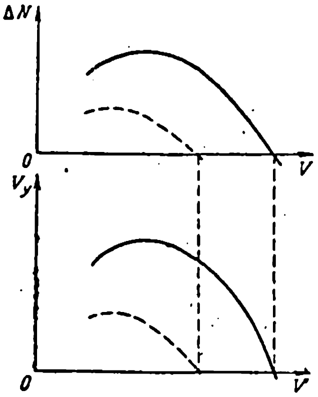

Figure 64. Power Margin ΔN and Vertical Velocity V_y as Functions of Forward Speed V in Various Configurations of an Aircraft. Solid line: gear and flaps up; dashed line: gear and flaps in landing position.

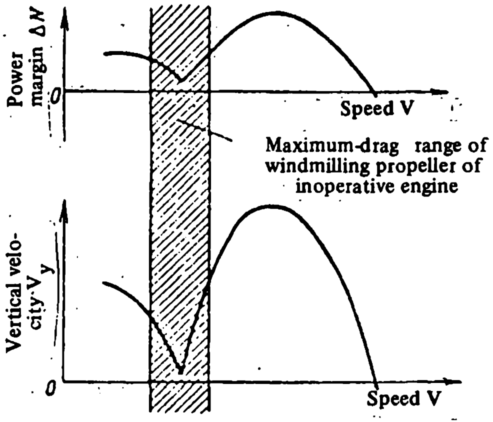

Figure 65. "Collapse" of an Airplane's Performance Data in the High-Drag Range of a Windmilling Turboprop Propeller.

comparatively little effect on the power margin, but it lowers appreciably the speed at which the power-margin maximum and the corresponding maximum possible vertical velocity occur. Lowering the gear, on the other hand, increases the airplane's aerodynamic drag directly without increasing lift, i.e., it lowers the lift-drag ratio and, along with it, all of the fundamental flight-performance data: speed range, vertical velocity, etc.

In the case of a windmilling propeller on a turboprop-engined aircraft, the effect of the change to landing configuration is compounded by another circumstance — the proximity of the speed at which the drag of the windmilling turboprop propeller reaches its maximum (see Fig. 26).

As we showed above (in Chapter II), the drag ("negative thrust") of an unfeathered windmilling turboprop propeller reaches its maximum at the speed at which the blades of the windmilling propeller come up against the intermediate stop. If this speed is close to that recommended for the landing approach with an aircraft of the particular type, it may be found expedient to deviate intentionally from this recommendation and maintain some other (higher or lower) speed at which the available power margin and hence also the vertical-velocity value will be more favorable (Fig. 65).

If the speed chosen is greater than that at which propeller aerodynamic drag has its maximum, it must be remembered that at /121 some stage during the approach, and most probably when speed is cut on the approach path, it will be necessary to pass through this drag peak in one way or another, and at this time the airplane will decelerate much more sharply than in the landing approach with fully operative powerplant to which the pilot is accustomed, or even an approach with a failed engine whose propeller is feathered.

2. LANDING ESTIMATE WITH PARTIAL AND UNBALANCED THRUST. LATERAL DEVIATIONS FROM RUNWAY PLANE. RUDDER DEFLECTION ANGLE MARGIN AT PULLUP

Even in the case least favorable from the standpoint of available power margin, in which an airplane cannot fly level in its landing configuration with one or more engines out, the possibility of executing a satisfactory landing is by no means excluded. However, procedures must be observed especially strictly in constructing the landing approach in such a case. The prime necessary condition for this is that the pilot be clearly aware of the fact that with the given number of running engines and given weight, his airplane can continue flying after lowering of the gear and flaps only with descent at a vertical velocity that is known beforehand.

Under such circumstances, the gear should be lowered only when the airplane is in a position that ensures that it will reach the airport, i.e., with consideration of altitude, the airplane's /122 vertical descent rate in its landing configuration, and the time required to lower the gear with both the main and the emergency systems. The time to start lowering the gear must be determined well in advance, before the approach to the airport, so as to ensure that it will be fully lowered on the final-approach path by the time the outer marker is passed.

Lowering of the gear any earlier may result in a forced landing before the airfield is reached. However, too-late lowering of the gear may result in no less serious consequences, especially on aircraft where this operation requires a comparatively long time. In this case, it may happen that the gear is still not all the way down at the time of touchdown.

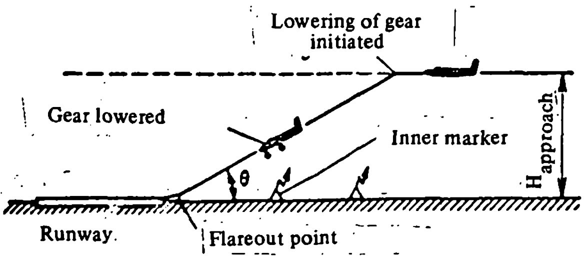

Figure 66. Determination of Time to Start Lowering Gear in Partial-Thrust Landing Approach.

In determining the gear-lowering time, it must be remembered that the gear lowering and retracting systems of many types of aircraft are powered from engine-mounted accessories (for example, from gear-driven hydraulic-system pumps). In such cases, failure of one or more engines will reduce the number of operative power sources supplying the landing-gear system, and this, in turn, may slow the operation down appreciably.

On other types of aircraft, however, advantage may be taken of the fact that the emergency gear-lowering system works faster than the main system (for example, if the main system is hydraulic and the emergency system pneumatic). In such cases, use of the emergency system despite the fact that the main system is operative will greatly speed up the lowering of the gear.

Figure 66 shows schematically the transition from level gear-up flight to descent at a certain vertical velocity after the gear is lowered.

Needless to say, if the airplane cannot fly level in the landing configuration with partial thrust, but descends at an angle smaller than the normal glide-path angle ($\theta < \theta_{glide}$), the problem is simplified greatly: it is sufficient to make the final transition to the landing configuration immediately before entry into the glide, and a thrust in excess of that which the airplane can still develop will definitely not be required during the rest of the glide. /123

It is best to lower the wing flaps to their takeoff position after entering the approach path. They should be lowered to the landing position in the vicinity of the inner marker, after the pilot has made absolutely certain that the airplane will reach the runway after full deployment of the flaps.

We repeat that the above recommendations pertain to the extremely rare case in which an airplane cannot fly level in the landing configuration with partial and unbalanced thrust.* However, when the available power margin supports level flight in any configuration of the airplane and there appear to be no limitations on the plotting of the landing approach, it is still advisable to come in on the approach path with the flaps in their takeoff (i.e., not fully deflected) position and maintain this position all the way to the outer marker. If the approach is successful, the pilot will always be able to deflect the flaps from the takeoff to the landing position before he approaches the runway — this operation requires only a few seconds. On the other hand, if the approach is incorrect, climbout for a second approach is naturally much easier with the flaps in their takeoff position than it would be if they were in the landing position.

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*For example, when more than the design number of engines fail late in a flight.

In all cases, whether with $V_{y\ max} > 0$ or with $V_{y\ max} < 0$, the best partial-thrust approach trajectory is that in which the airplane descends along the normal glide path to the intended flare-out point under some power, i.e., with the running engines operating at some intermediate setting.

This part-power approach has a number of advantages over descent with zero thrust from the running engines. Firstly, the pilot retains his freedom to maneuver in either direction: by varying the thrust of the running engines, he can either increase or decrease his descent rate and angle and thereby correct (with, of course, certain limitations) errors in either direction in the descent trajectory. Secondly, the running engines will respond better to the throttle at intermediate rpm than at idle, and, consequently, any required change in setting, up to and including a /124
change to maximum thrust for climbout, can be executed more quickly and cleanly.

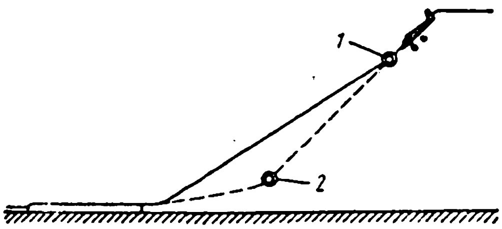

Figure 67. Trajectory of Landing Approach with Early and Late Correction of Error of Judgment. 1) Error detected in time corrected by slight change in engine thrust; 2) error detected too late requires a substantial change in engine thrust for correction.

The landing estimate for an airplane with partial and unbalanced thrust should be made in such a way that the airplane will fly slightly above the normal glide path or exactly on it, but never below it. This is because it is generally easier to correct an overshoot than an undershoot under the conditions of a part-power approach with partial thrust.

However, the above applies only under the mandatory condition that the deviations in either direction be small. If, on the other hand, an error of judgment has been committed and a considerable deviation from the normal glide path has accumulated, correcting it is rather complicated in either case – undershoot or overshoot. For this reason, the pilot must make an effort to correct any observed deviations as soon as possible – immediately after detection – with small adjustments to the settings of the running engines (Fig. 67). This mode of action is actually advisable in any landing approach, and not only in landings with partial and unbalanced thrust, but observance of the rule is especially important in the latter case.

With the approach to the runway, the excess over the normal glide-path altitudes should be reduced gradually, so that the airplane enters the normal descent trajectory at a height of 30-50 meters and approaches the airport at the usual angle to which the pilot is accustomed.

We noted above that correction of a substantial undershoot may prove to be simply impossible when the airplane is not capable of level flight in the landing configuration with partial and unbalanced thrust. However, correction of a large deviation in the /125 overshoot direction, especially with turboprop aircraft, may also involve certain difficulties and even give rise to dangerous situations. The latter arise from the fact that under these circumstances, the pilot makes a natural effort to correct the overshoot by recourse to the powerful decelerating factor available in the propellers of the turboprop engine. However, he must remember that this brake is so powerful that immoderate use of it may decelerate the airplane excessively and produce a rapid drop in speed. It may then be difficult to recover the normal speed needed to flatten out the descent and flare the airplane out in the proximity of the ground with unbalanced and partial thrust.

It must also be remembered that deceleration by use of the propellers of troboprop engines, especially the inboard ones, causes sharp deterioration of the wash over the tail and, consequently, of control-surface effectiveness. As a result, the pilot who uses propeller braking excessively at low altitude risks finding himself near the ground in an airplane that has not only lost speed, but is also difficult to control.

For these reasons, moving the propeller-pitch handle off its stop and pulling the throttle of a turboprop engine back past its flight-idle detent in order to adjust a landing estimate must be regarded as inadmissible both in landing approaches made under ordinary conditions, and especially in partial-thrust approaches.

Such are the landing-approach peculiarities associated with deficient magnitude of the thrust available to the pilot.

The behavior of the airplane is further complicated, however, by the imbalance with which this thrust is applied.

Aviation practice has recorded a number of cases in which the pilot making a landing approach with unbalanced thrust has come successfully out of the last turn into the plane of the runway and missed the runway. The specific cause of this effect was a spontaneous deviation of the airplane's trajectory ("drift" of the airplane) to one side of the runway plane. From time to time, attempts have also been made to explain such cases in terms of subjective errors committed by the pilot, e.g., it has been supposed that his attention drifted as he approached the final stage of unbalanced-thrust flight and he stopped paying the necessary attention to his direction of approach. Such explanations are not quite convincing, if only because it would appear that the pilot would have even greater reason to "relax" on approaching the end of a flight with all engines running, but there have been practically no recorded cases of missing the runway when the full power plant was available. In fact, the cases that have occurred after /126 partial powerplant failure are exhaustively explained in terms of the dynamics of unbalanced-thrust flight.

In fact, as we pointed out above, unbalanced-thrust zero-roll flight always involves slip toward the out engine. Here the slip angle is found to be larger the larger the unbalanced-thrust moment and the lower the flight speed.

A consequence of the latter is that during the landing approach, as the speed is gradually brought down to the value required for the flareout and the unbalanced-thrust moment $M_{u.t}$ increases because of the need to increase the thrust of the running engines to offset the drag that appears when the flaps and gear are lowered, the slip angle reaches its maximum values. As a result, the pilot unexpectedly finds the airplane drifting sharply to the side in a motion that it is no longer always possible to correct.

Any increase in the thrust of the running engines that is applied during the approach to correct the glide path results in additional drifting of the airplane off the runway plane in the direction of the out engines.

To avoid this, it is advisable to make an unbalanced-thrust approach without slip, i.e., with a slight roll toward the running engine. Here the roll must also be adjusted appropriately with each change in the thrust of the running engines. The pilot must remember a simple rule: more thrust means more roll, and less thrust less roll. Only when this rule is observed will the airplane approach the runway without being diverted off to one side.

It is particularly important to correct slip quickly by banking the airplane toward the running engine when an engine fails directly during the landing approach instead of at some earlier stage in the flight. True, the probability of failure during this period is extremely low, both because of its relatively short duration and because the powerplant is operating at comparatively low output during the landing approach.

Nevertheless, current standards require that the lateral stability and controllability characteristics of the airplane eliminate the possibility of its assuming dangerous angles of roll, slip, and attack on a sudden critical-engine failure during the landing glide in the landing configuration. Test results sometimes indicate that in order to satisfy this condition it will be necessary to make corresponding changes in handling characteristics, and, in particular, to specify a glide speed somewhat higher than that which would be adequate to ensure the required longitudinal-motion characteristics during a landing under /127 normal conditions (this speed is usually 1.3 times the minimum) all the way down to the flare point.

As a rule, the drag-lift ratios of most modern aircraft in the landing configuration are substantially larger than the slope of the normal landing-glide path. In fact, if $\theta = 2\text{-}4°$, then $\tan\theta = 0.04\text{-}0.07$, and $1/\tan\theta = 25\text{-}15$, which differs substantially from the usual values of K_{ldg}. For this reason, the landing approach is made not in a pure glide, but with some throttle, i.e., with the operative engines developing a certain amount of thrust, which is usually commensurate in magnitude with the cruising thrust. Consequently, an engine failure during the landing approach may also strongly influence flight performance. True, a failure during the landing approach is less dangerous from the standpoint of available thrust margin than it is at other stages in the flight. Its influence is felt more strongly in the controllability of the airplane. The potential hazard of such a failure consists in the fact that, as he continues the unbanked descent, the pilot senses the slip crabbing only at a very low altitude, when it is very difficult to counter and, in any event, requires execution of rather sharp maneuvers with partial and unbalanced thrust near the ground.

The above also applies in full measure to the automatic landing approach. If the automatic landing approach system is not programmed for the case of lateral-engine failure, the system will react to the slip-induced crabbing in the same way as to any other kind (for example, the crabbing that occurs under the influence of a lateral wind component). However, as we have shown, rudder-deflection margins are greatly reduced in flight at $\gamma = 0$ and $\beta \neq 0$. Therefore, in the event of lateral-engine failure during an automatic landing approach using a system not designed for this case, the airplane must be forced to bank toward the running engines or, if the system does not admit of such intervention, it must be switched off and the approach completed manually with observance of the "more thrust, more roll; less thrust, less roll" rule.

It goes without saying that in either manual or automatic control, the drift of the airplane off the runway axis toward the inoperative engine can be countered by an appropriate heading change. However, this technique is in some respects inconvenient. Firstly, it is more difficult to adjust the heading lead angle synchronously with thrust changes than it is to effect the corresponding roll change, since the former calls for execution of a more complex maneuver in two planes instead of one. In addition, it is generally necessary to close out the heading lead at the end of the flareout prior to touchdown. Even with symmetrical thrust, this maneuver requires rather precise execution, and with unbalanced thrust it is naturally still more complicated for the pilot. It is therefore more expedient to eliminate the lateral /128 drift of an airplane during a landing approach with unbalanced thrust by eliminating the slip directly, since it is the prime cause of this drift.

On four-engined aircraft, the thrust imbalance after failure of one engine can be greatly reduced during the landing approach by expedient utilization of the thrust from the running engines: First the total thrust is decreased by throttling back the engine having the symmetrical position on the other side. Only then, after its thrust has been reduced to the smallest possible value, are the symmetrically positioned running engines throttled back if a further decrease in total thrust is required.

During the approach to the ground, the airplane's speed must, as we know, be brought down gradually to the value required for the flareout. This fact also introduces certain additional peculiarities into the control of the airplane, primarily as a result of the aforementioned increase in the required rudder deflection angle.

Certain aircraft of the recent past that required moderate rudder deflection angles for steady smooth-configuration flight with unbalanced thrust began to require more than the available amount of rudder during the landing approach, and especially durings its last stage. Thus, at its normal ground-approach speed, one two-engined turbojet aircraft required that the thrust of the running engine be increased to $P \cong 0.85\text{-}0.9P_{max}$ for flareout. Thus, it would appear that the thrust margin fully supported correction of even a rather gross blunder. However, an unexpected impediment to control of the aircraft in the yaw plane then made its appearance. To hold to a straight line under these conditions, even with zero slip and an appropriate roll toward the running engine ($\gamma \sim \beta = 0$), the airplane required 27° of rudder deflection, while the amount available was only 25°.

The above might give the impression that the situation described was hopeless and that if the pilot bringing an aircraft of this type in to land permitted such a gross deviation from the glide path to escape his notice for so long a time, it would no longer be possible to get into the airport owing to the lack of the necessary means for countering the turn in the direction of the inoperative engine.

With all its complexities, however, this situation was in fact not hopeless.

To keep flying in a straight line on the flare path, it was only necessary to let the airplane slip in the direction of the running engine, for which purpose the airplane was rolled a few more degrees (2°-5°) in this direction. As we pointed out above (see Fig. 53), this reduces the required rudder deflection, thereby making it possible to steer the airplane in a straight line. /129

It may also be necessary to apply slip toward the running engine even when the pilot has not committed an error. The degree of thrust imbalance may be so high that the full deflection of the rudder is found inadequate to counter the yaw, even during a correct glide-path descent. An example of this situation is failure of two engines on the same side of a turboprop airplane with simultaneous failure of the feathering system of one or both of them (admittedly, an extremely rare case: not one has been recorded in aviation practice for some years now). Nevertheless, straight-line flight is generally possible even in this hypothetical case, but by only one method: applying slip toward the running engines. A slight excess of roll is helpful here, so that the airplane will fly straight with only partial deflection of the rudder. At least 20-30% of the rudder deflection must be left in reserve for countering of random atmospheric disturbances and for preventing the airplane from yawing at flareout, when speed and hence also rudder deflection margin are reduced even further.

During the flareout, the airplane should never be kept from yawing by cutting the thrust of the running engine, not even to handle a deficiency of rudder deflection margin that reappears for the same reason. Their thrust can be reduced only after the airplane has been levelled off and is in its flare. Although the pilot may be able to keep the airplane from yawing by reducing the thrust of the running engines before the airplane has flattened out, he risks seriously disturbing the correctness of the landing profile and may even drop the wheels sharply onto the ground.

It must also be remembered that on aircraft with irreversible hydraulic boosters and spring loaders in the directional-control system, the increase in the required rudder deflection near the flareout point may also involve a corresponding increase in pedal effort.

After the airplane has flared out, the throttles of the running engines should be moved back smoothly, with simultaneous recovery of the airplane from the roll.

Here it must be remembered that the rudder trim tab, which /130 has been adjusted during flight for zero effort with the rudder deflected, will now cause an effort of the opposite sign to appear at the pedals. It is therefore necessary to return the tab to a near-neutral position beforehand, before the flareout, and then, as long as the operative engines continue to work, to hold the rudder in the proper position by applying the necessary pedal effort, or to be ready for the appearance of an approximately equal effort at the opposite pedal on the flare path after the operative engines have been reset to idle. Psychological difficulty is encountered in dealing with this phenomenon if the pilot nas not been expecting it, because it requires readjustment of his program of operations: the yaw overshoot takes place in the direction of the running engines, after the pilot has been working to counter a yaw toward the out engines throughout the entire time of unbalanced-thrust flight. Whenever possible, therefore, it is advisable that the rudder tab be returned to a near-neutral position beforehand, i.e., before the running engines are idled down.

3. LANDING APPROACH WITH PARTIAL AND UNBALANCED THRUST IN A CROSS WIND. INTENTIONAL UNBALANCING OF THRUST TO COUNTER THE EFFECT OF A CROSS WIND

The problem of directional control on the landing-approach path boils down essentially to keeping the descent path in the plane of the runway by countering random factors that tend to divert the aircraft from this plane. The presence of a lateral wind component complicates this task appreciably, even in a descent with the powerplant in full working order.

Problems involved in cross-wind landings have recently acquired much greater importance than they had at earlier stages in the development of aviation. This is because the cross-wind landing has been transformed in our time into a much more frequent event than it was in the past, when airfields were generally circular or square in shape, so that all takeoffs could be made into the wind. The appearance of high-speed jet aircraft with long takeoff and landing distances dictated a universal trend to concrete runways, thus leaving only two possible landing headings on each runway available at a given airport. Although these strips are usually placed in the most probable wind direction, that corresponding to the orientation of the "wind rose" plotted for the locality in question, a wind blowing straight down the runway is /131 now the exception rather than the rule.

The greatest difficulties are encountered in the landing approach and landing of swept-wing aircraft in cross winds. These aircraft practically prohibit the until-recently routine method of putting the airplane into slip in order to counter wind crab. This is because, unlike straight-wing aircraft, swept-wing types in slipping straight-line flight at relatively large angles of attack (and it is such angles that are assumed during the landing approach and especially at the actual landing) develop strong aerodynamic moments about their longitudinal axes that tend to bring the airplane out of roll and slip.

To hold the aircraft in the necessary attitude, the pilot must apply a strong aileron deflection in the direction of the slip. This deflection reaches its limit even at comparatively small angles β, so that a further increase in slip becomes impossible, not to mention the fact that this leaves the pilot no aileron-deflection margin with which to counter random external disturbances.

The original cause of this situation consists in the fact that the absolute magnitude of the transverse static stability coefficient m_x^β of the swept wing depends strongly on angle of attack, unlike that of the straight wing. Figure 27 illustrated the trend of this relationship. We saw from this figure that the absolute value of the coefficient m_x^β varies manyfold in the normal range of angles of attack of a swept-wing aircraft. Naturally, the wing dihedral is adjusted during the design and trials of the aircraft to preserve transverse static stability (i.e., observe the condition $m_x^\beta < 0$) in all cases. As a result, even when acceptable, near-zero coefficients m_x^β are ensured at small angles of attack, it is necessary to accept the fact that a swept-wing aircraft will have a substantial excess transverse static stability at near-landing and landing angles of attack.

Hence the use of slip as the sole or even as the main instrument for countering cross winds in the landing approach for swept-wing aircraft would place a severe limitation on the maximum cross-wind speeds at which such aircraft could be landed at all.

Because of this, a different piloting technique is now used on most swept-wing aircraft types during landing approaches in cross winds. Slip is not used (or is used only as an auxiliary); /132 instead, the drift that occurs is countered entirely or almost entirely by introducing an appropriate lead into the heading.

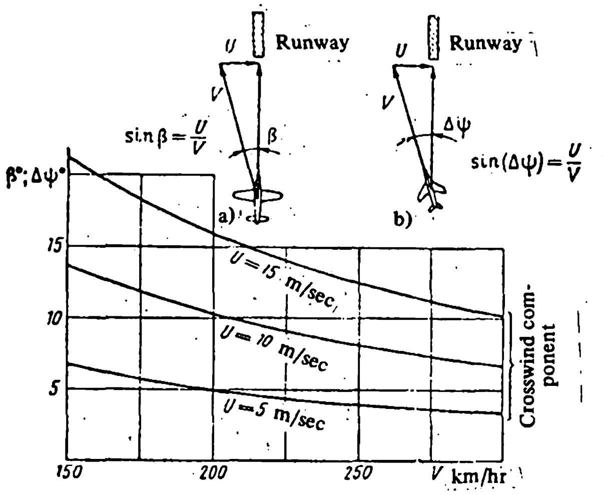

Figure 68. Two Methods of Countering Crosswind Drift in Landing Approach. a) With slip; b) with heading lead.

This technique has a number of important advantages. First, there is practically no limit on the magnitude of the lateral wind component with which a landing approach is possible, because diversion from the landing heading through any necessary angle introduces no essential complications into the work of piloting. Secondly, during a nonslipping landing approach, the airplane is washed symmetrically by the airstream and its rudder and ailerons are in near-neutral positions; therefore, the full deflection margin is retained in both directions for countering of random external disturbances.

Figure 68 illustrates schematically both of the above cross-wind landing-approach techniques. If the approach is made with a heading lead, the airplane must be turned to the landing heading before it actually touches down, so that the velocity vector is aligned with the plane of the wheels or at least so that the angle between them is reduced substantially in order to avoid heavy lateral loads on the main wheels and the undercarriage structure. However, even in landings with uncorrected slip, these loads do not generally exceed the ranges provided for other design cases, e.g., the "ground loop." Thus, the aligning turn into the runway plane /133 may be omitted in many cases, or executed after touchdown, since most modern tricycle-gear aircraft perform this turn spontaneously, independently of pilot actions. After its main wheels touch the ground, an aircraft of this configuration tends to straighten itself out under the action of the moment generated about its center of gravity by the lateral components of friction at the main wheels.

In essence, the capability of an airplane to orient itself to the runway axis is a manifestation of the directional stability characteristic for aircraft with nose wheels in their motion along the ground. Needless to say, use should be made of this property only when it is certain that the strength of the tires and the airplane's entire undercarriage permit the application of the lateral load that appears when its wheels touch the ground at an angle of crab. After a landing approach in which the crab due to the cross wind is countered by the heading-lead technique, therefore, pilots usually still make the controlled correcting turn of the airplane into the plane of the runway before touchdown, so that if the landing cannot be made without the least amount of crab relative to the ground, the latter will at least be greatly reduced.

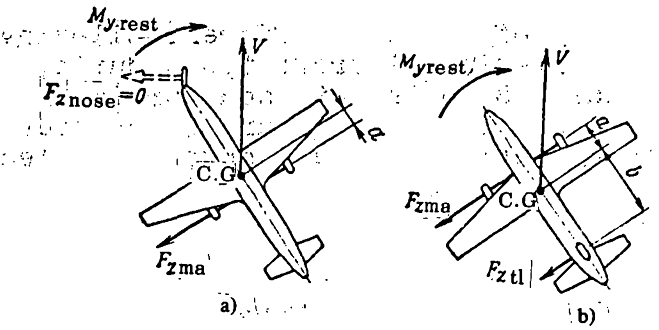

Figure 69. Yawing Moment from Transverse Component of Wheel Friction. a) Landing of aircraft with nose wheel with crabbing relative to the ground; b) landing of aircraft with tail wheel with crabbing relative to ground.

But even this does not greatly complicate piloting, owing to the absence of any stringent requirements as to the precision with which the slip is corrected at the moment of touchdown.

On aircraft of older configurations (with tail wheels), this requirement applied in full force and all applying landing rules were subordinated to its satisfaction. The reason for this was that aircraft with tail wheels had low directional stability in motion along the ground, and a strong initial impulse like the moment of the lateral friction of the main wheels against the ground that inevitably occurs in a crabbing landing could (and often did) result in a progressive uncontrollable turn. /134

For an airplane with a tail wheel (Fig. 69b),

$$M_{y\,\text{rest}} = F_{z\,\text{ma}}a - F_{z\,\text{tl}}b,$$

where $F_{z\,tl}$ is the lateral friction of the tail wheel and b is the distance from the airplane's center of gravity to the tail wheel.

Two cases are possible here.

If $|F_{z\,mn}a| < |F_{z\,tl}b|$, $M_{y\,rest} > 0$ and the airplane is oriented along the runway axis after touchdown, i.e., it behaves like an airplane with a nose wheel.

If $|F_{z\,mn}a| > |F_{z\,tl}b|$, $M_{y\,rest} < 0$ and the airplane goes into a turn.

On the other hand, aircraft with nose wheels (this gear design prevails in the modern aircraft pool almost without exceptions) have such high degrees of directional stability in motion along the ground that they are practically immune to uncontrollable turns during rollout no matter what the magnitude of the initial impulse:

$$M_{y\,rest} = F_{z\,mn}a,$$

where $M_{y\,rest}$ is the restoring directional moment of the landing gear, $F_{z\,mn}$ is the lateral friction force of the main gear (the nose wheel has zero lateral force, since the nose-wheel strut is self-orienting), and a is the distance from the airplane's center of gravity to the axis lines of the main landing-gear struts.

$M_{y\,rest} > 0$ in all cases, i.e., it tends to bring the airplane's axis into line with the velocity vector.

On modern aircraft, therefore, the adjusting turn before touchdown after a landing approach with heading lead is executed only in the interest of reducing the lateral loads on the landing gear, and not to ensure the necessary controllability during the subsequent motion along the ground; therefore it does not require special precision of execution and is, in any event, less complex for the pilot than the recovery from roll and slip that would be required directly above the runway in an approach with slip.

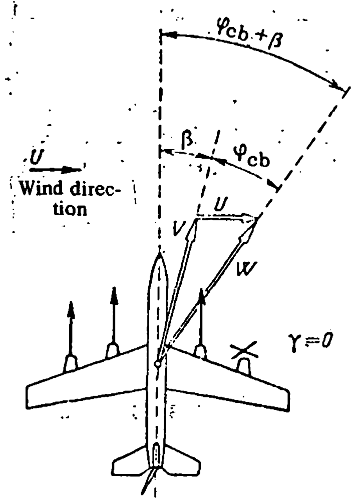

Figure 70. Addition of Angles of Crab Due to Slip and to Cross Wind During Unbalanced-Thrust Landing Approach Without Roll. /135

Irrespective of the technique used to counter cross-wind crabbing – heading change or slip – execution of this maneuver with unbalanced thrust introduces its own additional complications. Figure 70 illustrates the case that is most complicated and least desirable under these circumstances: an unbalanced-thrust approach without roll (and, consequently, with slip) in the prssence of a cross wind from the side of the running engines. As the figure shows, the crab due to the cross wind has the same sign as the crab due to slip in this case. As a result, the total amount of crab relative to the ground may become quite substantial – ranging into the tens of degrees of angular measure. In an unbalanced-thrust approach without roll and in the presence of a lateral wind component with respect to the runway axis, therefore, it is always advisable, whenever possible, to choose the approach direction such that the wind will be blowing from the side of the out engines. This will result in different signs of the cross-wind crab and the crab due to the slip associated with unbalanced-thrust flight without roll, and they will therefore offset one another at least partially. The above statement is valid, of course, only if the longitudinal component of the wind is not so large that landing in the direction preferable from the standpoint of countering the lateral drift would be dangerous owing to a high tail wind.

The possibility of mutual cancellation of the cross-wind crab and the crab due to unbalanced-thrust slip gave rise to the idea of intentionally unbalanced application of thrust in the interest of counteracting cross-wind crab in flight with the airplane's powerplant in full working order. To make this idea workable, it would be necessary to run the airplane's engines at unequal settings during the landing approach: the engines on the side from which the wind is blowing would have to develop less thrust than those on the opposite side.

If the problem is that of exact cancellation of cross-wind crab by using slip to develop a lateral velocity component equal in magnitude to it but opposite in sign, it is necessary, as we see from Figs. 46 and 68, to generate an unbalanced-thrust moment that satisfies the equation

$$\phi_{cb} = \beta .$$

Or, recognizing that $W/V = \sin(\phi_{cb}) \cong \phi_{cb}$ and $\beta = Z/c_z^\beta qS$, where $Z = \frac{z}{l_{v.t} - l_1}\Delta P$ and, consequently, $\beta = \frac{z}{l_{v.t} - l_1} \cdot \frac{\Delta P}{c_z^\beta qS}$, we obtain /136

$$\frac{W}{V} = \frac{z}{l_{v.t} - l_1} \cdot \frac{\Delta P}{c_z^\beta qS},$$

whence

$$\Delta P = \frac{l_{v.t} - l_1}{z} \cdot \frac{W}{V} c_z^\beta qS = \frac{l_{v.t} - l_1}{2z} W c_z^\beta \rho V S. \qquad (10)$$

Here ΔP is the required thrust difference between symmetrical port and starboard engines for compensation of the cross-wind drift by slip without roll, W is the lateral component of the wind, V is the forward velocity of the airplane, c_z^β is the static derivative of the transverse-force component with respect to angle of slip, $l_{v.t}$ is the lever arm of the vertical tailplane, z is the distance from the line of action of engine thrust to the airplane's plane of symmetry (the engine lever arm), l_1 is the distance from the application point of the lateral aerodynamic force Z to the airplane's center of gravity, q is the ram pressure, ρ is the mass density of the air, and S is the wing area.

The above formula permits accurate determination of the degree of thrust imbalance necessary under a given set of conditions to counteract the crab due to a cross wind of given force.

In practice, however, there is no need for such exact cancellation of the cross-wind crab. Moreover, the wind speed itself and the direction of the wind are seldom so stable as to justify formulation of such a problem. In practice, it is usually sufficient to reduce the crab to the point at which the pilot cannot perceive it visually, i.e., to eliminate the apparent cross-wind crab. Nevertheless, the visual approach is made easier by calculation of the thrust imbalance required for a given cross wind before the approach to the landing airport.

Use of this method makes it possible to broaden the range of crosswind speeds in which an airplane of the particular type can be landed.

Thus, the flight manual for the Tu-104 airplane states that with the two engines developing balanced thrust, the maximum permissible cross wind at landing is 12 m/sec, but that it increases to 14 m/sec when the thrust of the engine on the side opposite to that from which the wind is blowing is increased.

It is easily shown that use of this method is even more effective, increasing the range of permissible cross-wind speeds not by 2, but by 4-5 m/sec and more, for aircraft with engines /137 farther outside the plane of symmetry (such as the Tu-144, An-22, and others); naturally, this means a considerably broader range of operational capabilities for aircraft of these types.

While on the subject of intentional disturbance of thrust symmetry, we should take note of certain admittedly quite rare aircraft types in which this disturbance resulted from the very accommodation of the powerplant. The single engine of the Blohm und Voss BV-141 airplane (1944) was situated not in the machine's plane of symmetry, but off to one side of it, on the wing.

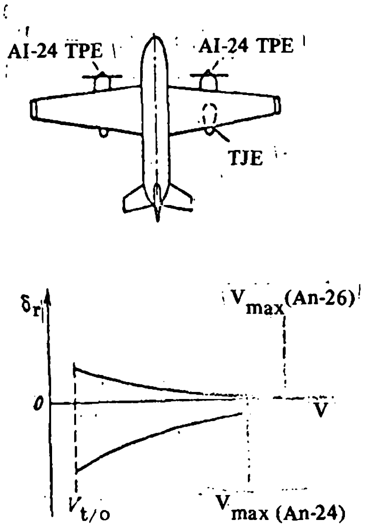

Figure 71. Plan View of An-26 Airplane and Dependence of its Rudder Deflection on Flight Speed (as Compared to An-24).

The An-26 aircraft, which resembles the An-24 in design but differs from it in particular in the presence of a third engine — a turbojet mounted in the starboard engine nacelle — is now being flown successfully. In itself, installation of the third engine substantially improves the performance of the airplane during takeoff and climbing and, of course, in the event of failure of one of the main engines. Simultaneously, this engine replaces the self-contained auxiliary powerplant used to supply power to the airplane on the ground (in particular, to start the main engines).

As for the unsymmetrical position of the turbojet engine, this was chosen, firstly, from design considerations (proximity to the fuel tanks and other powerplant systems) and, secondly, because the two symmetrically positioned AI-24 turboprop engines do not yield fully symmetrical total thrust as a result of the twist of the wash from their propellers. As a result, the An-24 airplane has a tendency to turn to the right that is especially strongly pronounced at low flight speeds with the engines running at full power.

The unsymmetrically applied thrust of the turbojet more than offsets this tendency and generates a yawing moment of approximately the same magnitude but in the opposite direction — to the left. As a result, as Fig. 71 shows, the An-26 airplane requires a deflection of the rudder pedals in flight that is nearly equal in magnitude but opposed in sign to that required by the An-24. Thus, flight with less than fully symmetrical thrust is /138 the normal operational case, and not a special one, on certain types of aircraft.

4. CLIMBOUT WITH PARTIAL AND UNBALANCED THRUST

In those cases in which the pilot has made late or disproportionate use of the measures available to him for adjustment of the landing estimate (these measures reduce basically to variation of powerplant thrust on modern aircraft), the uncorrected error in the estimate will result in the airplane's approaching the ground not at the intended flareout point, but at some other point located more or less distant from the beginning of the runway.

An error in the position of the flareout point will also shift both the point of touchdown and the end of the landing roll. The need to reckon with the possibility (and even the inevitability) of such errors is one of the factors that have led to the construction of runways with a certain length margin beyond the distances corresponding to the takeoff and landing characteristics of the aircraft to be operated in and out of the particular airport.

Within certain limits, therefore, scatter of the touchdown points of aircraft relative to the landing markers is normal. However, if the error in the landing estimate exceeds the permissible limits, especially on the overshoot side, to a degree such that its correction is no longer a practical possibility and cannot guarantee that the rollout will end with the airplane still on the runway, the pilot must make a so-called climbout for a second approach. For this purpose, the powerplant is set to takeoff power (a lower, e.g., the nominal setting may sometimes be adequate if the climbout is started early enough and if the airplane has certain speed and altitude margins). If the speed of the airplane has already been brought down below the value established for transition to climbing after takeoff, it is again increased to the latter value. The vertical rate of descent is brought down until the airplane has levelled out and begun to climb; this is followed by a second landing approach. It should be noted that even with the entire powerplant functioning normally, a climbout, like any maneuver executed in the immediate proximity of the ground, requires quite crisp and well-timed actions on the part of the crew. In particular, the vertical descent rate must be zeroed out without delay, but at the same time it is absolutely necessary to maintain the necessary forward-speed margin.

Nevertheless, climbout presents no substantial piloting dif- /139 ficulties under normal conditions, and it is in any event safer than landing with a gross error in the estimate. However, certain complications are encountered in a landing approach with partial and unbalanced thrust when a climbout becomes necessary.

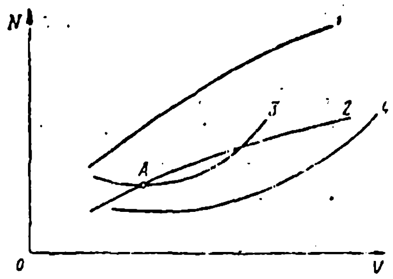

Figure 72. Required and Available Thrust Curves of Airplane with Full and Partial Thrust in Flight and Landing Configurations. 1) Available thrust with powerplant in full working order; 2) available thrust with partial powerplant failure; 3) required thrust in landing configuration; 4) required thrust in flight (cruising) configuration.

Most important among these complications is the fact that the power (thrust) margin is further reduced from that available in route flight with partial thrust. To estimate the degree of this decrease, it must be remembered that not only is the available thrust reduced as a result of failure of some of the engines, but the required thrust is also increased appreciably at the same time as a result of putting the airplane into its landing configurations (lowering the gear and application of full flaps). Consequently, if the range of possible flight speeds with acceleration (or a positive vertical velocity) was enclosed between curves 1 and 4 (Fig. 72) in flight with the gear and flaps up and the powerplant performing normally, this range narrows to the dimensions of the zone enclosed between curves 2 and 4 after failure of some of the engines, and, after lowering of the gear and flaps, to the segment between curves 2 and 3, which is even more confined both along the abscissa (speed range) and along the ordinate (power margin).

There are aircraft that lack even this small range in the landing configuration after failure of a certain (above-design) fraction of their powerplants. This means that they are totally incapable of climbing out when a particular number of engines have failed – say two of the existing three. In flying an aircraft of a given type, the pilot must be fully aware of the conditions (flight weight, number of out engines, setting of their propeller blades, flap deflection angle δ_f, etc.) under which this airplane can execute a climbout and second landing approach in the event of an unsuccessful first approach.

To endow an airplane with climbout capability with some engines out, provision is sometimes made for execution of the partial-thrust landing approach with the wing flaps less than fully deflected ($\delta_f^0 < \delta_{f_{ldg}}^0$). This helps increase the available thrust margin, although it also increases V_{ldg}. /140

In principle, an airplane's climbout capability can be restored by such measures — taken simultaneously with application of takeoff power — as retracting the landing gear to reduce aerodynamic drag and, consequently, the required thrust, and the accelerating descent (the latter, of course, only if the climbout is begun at adequate altitude).

The acceleration of the motion on an inclined path is expressed by the formula

$$j = g\left(\frac{\Delta N}{VG} \pm \sin\theta\right),$$

where the plus sign in front of the second term in the parentheses corresponds to acceleration with loss of altitude, in which the weight component helps increase speed. On the other hand, the minus sign in front of this term applies for climbing acceleration, in which the weight component works against speed increase. In the case of level acceleration, the sine of the path inclination angle naturally vanishes.

Modern civil and military aircraft have practically no need to accelerate (much less descend) in order to execute a climbout owing to the mandatory thirty-percent excess of the landing-approach speed over the stalling speed.

It is generally known that a premature pullout for a second approach presents a serious danger because of the possible loss of speed. This applies in particular to climbouts with partial thrust.

As the above formula shows, the acceleration is directly related to the power margin ΔN, which is substantially below normal in a partial-thrust climbout. This makes it necessary to initiate the partial-thrust climbout in good time, at an altitude somewhat higher than the minimum climbout-decision altitude established for the particular type of aircraft in landing approaches with the powerplant in full working order.

The abnormally small acceleration, and the correspondingly small longitudinal g-force n_x sensed by the pilot in a partial-thrust climbout may give him the false impression that the powerplant has failed totally.

This error is most probable on aircraft whose engines are mounted on the fuselage tail section. In this design, the noise of the running engine is so faintly audible on the flight deck that it is difficult to distinguish against the background of slipstream noise. At the same time, most modern gas-turbine engines are characterized by relatively sluggish throttle response — the time for them to accelerate from idle to takeoff or maximum /141 power sometimes exceeds ten seconds.

Taken together, all of these factors may cause the pilot to read the slowness of the running engines to come up to full thrust as an indication that full thrust is not forthcoming. With this possibility in mind, the pilot must not rely fully on his senses (perception of longitudinal g-force, audibility of engine noise, etc.) in operating the engines for a climbout, but must check the runup of the operative engines to the necessary power against the available instruments — tachometers, turbine-outlet gas-temperature gauges, thrust or torquemeters, etc. (personally or through reports from other crew members).

The above applies, of course, not only for a climbout, but also for the pullup during the landing approach and, in general, to control of the powerplant in any stage of flight. However, observance of this rule is especially important in a partial-thrust climbout owing to the presence of the unfavorable combination of small available longitudinal acceleration on the one hand and a shortage of time on the other.

As is shown by the curves in Fig. 72, the range of flight speeds with partial and unbalanced thrust is narrowed with the gear and flaps in their landing positions not only by the decrease in top speed, but also by a marked increase in the minimum speed. In other words, when the required and available thrust and power curves are shifted, their points of intersection move closer together: the right-hand intersection point shifts to the left and the left-hand intersection point to the right. In the range of low flight speeds, therefore, there may exist a region (to the left of point A on the figure) in which the development of a positive acceleration in level flight with partial thrust is not possible. If he enters this speed range with partial thrust and needs to climb out, the pilot will not be able to execute this maneuver (unless, of course, he has a considerable altitude margin for descending acceleration). The complexity of the situation that has developed may be further aggravated by the fact that the impossibility of climbout is unexpected: just previously, after all, the airplane had definitely been capable of level or even climbing flight, having a velocity higher than that at point A in /142 the same configuration and with the same thrust deficiency. To avoid entering into this range during a partial-thrust landing approach, remembering that a climbout may become necessary on any approach, flight speed should not be lowered below the value corresponding in the landing configuration to the boundary between flight conditions one and two until it is certain that the landing estimate has been successful.

In the range of condition two, required power increases sharply and the airplane lacks even the small power margin that was available in flight condition one.

Observance of the approach conditions called for by the applicable manuals guarantees that the airplane will not enter this unsafe range. This circumstance must be stressed as another illustration of the generally known proposition that the lowest speeds that are allowed to develop in various flight situations (at a given weight and configuration of the airplane, etc.) generally greatly exceed the minimum (stalling) speed.

In executing a climbout with unbalanced thrust, it must also be remembered that everything said above (in Sec. 2 of this chapter) concerning the pullup with unbalanced thrust also applies in full and, as a rule, even more conspicuously to the case of climbout. This is because the unbalanced-thrust moment is larger in magnitude in a climbout than on pullup, during which the running engines are usually reset to some intermediate output and not to takeoff power.

As a result, the rudder-deflection margin and pedal effort may prove to be more critical during a climbout than during pullup.

The technique used to overcome these difficulties remains the same: a slight roll of the airplane toward the running engines provides the necessary decrease in both the rudder deflections required to maintain straight-line flight and in the accompanying pedal effort. In contrast to the pullup, the latter may be reduced during a climbout by deflecting the rudder trim tab.

The above aspects of the climbout make it one of the most critical elements in flight with partial and unbalanced thrust, one that requires special alertness and sure responses from the pilot and his strict observance of the recommendations arrived at from the flight-test data for the particular type of airplane, in particular the stated speed values, wing-flap positions, and the minimum altitude at which the pilot has the climbout option.

5. LANDING ROLLOUT WITH PARTIAL AND UNBALANCED THRUST /143

As a rule, an airplane executes its landing roll with the engines running at idle or zero thrust. Thus there should apparently be no difference at this stage in the flight between an airplane with a fully operative powerplant and an airplane that has been landed with one or more engines out. Actually, however, an airplane with some engines out of operation retains certain differences from the fully operative airplane in certain respects even during the rollout, and highly undesirable consequences may follow if they are ignored.

We pointed out above (in Sec. 2 of this chapter) that it is desirable during the landing approach to turn the rudder tab to a neutral or near-neutral position when it has been deflected in unbalanced-thrust flight through the angle necessary to relieve the pedal effort.

In many cases, this recommendation can be followed only in part. Thus, if the effort is so great in unbalanced-thrust flight with the trim tab in neutral that it impedes precise and commensurate pilot actions, it is necessary during the approach to the ground to return the trimmer not to neutral, but to some intermediate position at which the pedal effort on the last segment of the approach to the ground remains within surmountable limits. Such a situation is illustrated in Fig. 73. Suppose that it was necessary in unbalanced-thrust flight to give the rudder a certain deflection δ_{r1} and apply the corresponding effort P_{r1} at the pedals. To reduce the pedal effort to zero at this deflection, the pilot deflected the trim tab through an angle τ_{r1}. As he approached the ground, the pilot reset the tab to a position τ_{r2} somewhere between τ_{r1} and $\tau_r = 0$. To maintain the necessary rudder deflection δ_{r1}, he was obliged to apply an effort P_{r2} to the pedal. After the thrust of the running engine was cut prior to landing, it was necessary to return the rudder to a near-neutral position ($\delta_{r0} \cong 0$) in order to keep the airplane moving in a straight line. If the rudder tab were also in neutral, the effort at the pedals would also be near zero. But since in our case, for the reasons set forth above, the tab was reset not to neutral, but to some position τ_{r2} intermediate between τ_{r1} and neutral, the pilot, having throttled back, finds it necessary to overcome a new force P_{r3} in the direction opposite to that which he had overcome before throttling back.

The sign reversal of the rudder-pedal effort, coming after the entire period of unbalanced-thrust flight, during which the pilot was kept very busy fighting a tendency to yaw toward the out engine, requires a certain amount of rather fast internal reorientation. Any delay may result in a turn toward the running engine during the rollout. /144

A number of devices are used on modern aircraft to hold to the direction of rollout: the rudder (basically at the early stages in the rollout, when the speed is still relatively high and the aerodynamic control surfaces have not lost effectiveness), main-wheel brakes, the steerable nose truck of the landing gear, and engines situated outside the airplane's plane of symmetry, which the pilot can set to various rpm (thrust outputs) as desired.

In a rollout with partially inoperative powerplant, the last-named of the above devices for holding the roll in a straight line is not available, or, in any event, the possibilities for its use are severely limited. Partial retention of directional-control capability with the engines during the rollout is possible only

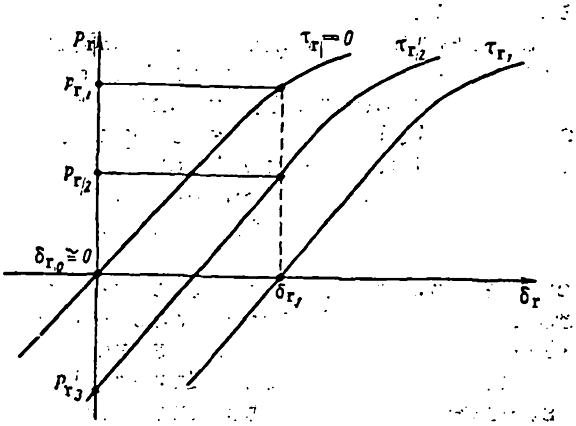

Figure 73. Pedal Effort P_r as a Function of Rudder Deflection Angle δ_r with Various Trim-Tab Positions (Illustrating the Causes of Yaw Toward the Running Engines at Landing in the Case with $\tau_r \neq 0$).

if at least one symmetrical pair of engines has remained operative (for example, both inboard or both outboard engines of a four-engined airplane).

The flight manuals for most turboprop-engined aircraft have been written with a view to ensuring the highest possible symmetry of deceleration by the propellers, by taking them off their intermediate detents on the ground and resetting the engines to ground idle thrust. Thus, for example, if the No. 1 or /145 No. 4 engine of a four-engined turboprop airplane has failed, the propellers of the No. 2 and No. 3 engines provide deceleration over most of the rollout. Deceleration with the propeller on the engine symmetrically opposite to the out engine is in all cases (and especially on two-engined aircraft) strictly regulated according to speed, down to the point at which the propeller is taken off its detent and the engine itself is reset to ground idle at the end of the rollout, at a speed of about 40-60 km/hour.

Here it is also necessary to take account in each specific case of the conditions under which the directional-control elements — the nose-wheel truck and the main-wheel brakes — work on the ground. In executing a landing with unbalanced thrust on a wet or icy runway, special attention should be given to maintaining balance between the propeller drags of the running and nonrunning engines (or, more precisely, to keeping the inevitable imbalance from exceeding the permissible limits).

Yet another circumstance must be remembered in regard to the landing of turboprop aircraft with unbalanced thrust. An inoperative engine of a piston-engined or turbojet aircraft continues to develop a certain amount of drag — though a substantially smaller amount than in flight — during the landing roll, and the running engine symmetrically opposite to it also develops a certain amount of thrust even at idle. With propeller-driven and turbojet aircraft, therefore, the tendency to turn toward the inoperative engine will persist during the rollout, although, needless to say, it will be much weaker than it is flight.

The turboprop airplane is another matter. If the propeller of the inoperative turboprop engine is feathered and the running engine symmetrically opposed to it is reset to ground idle, the drag of the feathered propeller is found to be smaller than the propeller drag of the idling engine, especially if the propeller is off its intermediate detent. As a result, the turboprop airplane develops a tendency to turn not toward the inoperative engine, but toward the running engine during the landing roll.

As we have shown, this tendency can be offset by the means available to the pilot, but only provided that it does not come as a surprise to the pilot. Otherwise, the change from a tendency of the airplane to turn in one direction to the direct opposite may cause the airplane to swerve suddenly to one side, and perhaps even run off the runway.

Chapter V /146

TAKEOFF WITH PARTIAL AND UNBALANCED THRUST

1. GENERAL CHARACTERIZATION OF TAKEOFF WITH PARTIAL AND UNBALANCED THRUST. TWO TAKEOFF-RUN PILOTING TECHNIQUES COMPARED IN THE CASE OF ENGINE FAILURE

In aviation practice, a takeoff with partial and unbalanced thrust is regarded in almost all cases only as a last resort. Such takeoffs may be made if one of the engines fails at a point during the takeoff run at which aborting the takeoff is no longer a practical possibility or would definitely involve a greater risk than lifting off with partial and unbalanced thrust. The deliberate takeoff with partial and unbalanced thrust is an extremely rare exception and will be discussed separately below.

Engine failure during takeoff has long been correctly regarded in aviation as one of the most complex and dangerous special situations that a pilot can encounter. True, the probability of such failure at the present reliability level of aviation powerplants is negligibly small. The takeoff of an airplane requires a relatively very short time, on the order of tens of seconds. It is even less probable that an engine failure, which is a highly improbable event to begin with, could occur presisely during this very short time interval, the more so since takeoff is immediately preceded by thorough inspection, checking, and performance-testing of all engines, a procedure that lowers even further the probability that a significant defect will make its appearance in one of them during the first few minutes after its performance. With gas-turbine-engined aircraft, which have powerful braking systems, there is an opportunity to run the engines at takeoff or near-takeoff power with the airplane at a standstill, thus verifying the condition of the powerplant immediately before starting the takeoff run, at the same setting at which the engines will be running during takeoff. /147

Taken together, all of the above greatly improves the performance reliability of the airplane's powerplant during the critical takeoff stage in the flight. Nevertheless, the possibility of engine failure during takeoff may not be ignored altogether, and for this reason the pilot must always be fully prepared, both technically and psychologically, to act confidently and without errors in such event. The very categorization of various pilot actions as error-free (or, on the contrary, erroneous) must not be based on any sort of qualitative estimates, but on the results of extended flight tests that have been worked up to specific recommendations and the corresponding strictly defined instructions.

Particular importance attaches to study of the takeoff with partial and unbalanced thrust as a design case that certainly exceeds in complexity any other practically possible flight situation arising out of partial powerplant failure.

Actually, at least three complicating circumstances arise simultaneously on failure of a lateral engine during takeoff:

- the largest absolute value of the unbalanced-thrust moment $M_{u.t} = P \cdot z$, owing to the fact that $P = P_{max}$ during takeoff;

- lowered effectiveness of the controls (especially in the directional plane) owing to the low speed;

- the most stringent requirements as to the trajectory and dynamic parameters of the motion that follows.

While a temporary deviation of the airplane from the initial values of speed, altitude, roll, and yaw, with a subsequent return to steady values of these parameters (and, in a number of cases, e.g., speed and altitude, even lower-than-initial values) may be permitted after an engine failure at a certain stage in steady flight, the direction of motion along the runway axis must be kept practically unchanged during takeoff, and the longitudinal acceleration must ensure that the normal takeoff distance will not be exceeded if the takeoff is continued or that the airplane will stop on the remainder of the runway if the takeoff is aborted.

Therefore, for an airplane whose controllability and power reserves provide for a favorable outcome in the event of partial thrust failure during takeoff, assuming correct responses on the part of the crew, this outcome will be the more favorable if a lateral engine fails in any other flight conditions; this gives grounds for regarding the first of the aforementioned cases as the design case.

Failure of one engine is taken as the design case in investigating takeoffs with partial and unbalanced thrust for aircraft with from two to four engines, i.e., in effect for most of the world's aircraft. /148

This assumption is backed up by the extensive statistical material available, according to which such a coincidence as failure of two engines independently of one another during a time interval of a few tens of seconds is so highly improbable at the present service lives and reliabilities of aircraft engines that it need not be reckoned with in practice. This applies, of course, only provided that the engines mounted on the airplane and their systems (fuel-supply, lubrication, air-intake, engine-control, and others) are indeed mutually independent and, consequently, simultaneous or nearly simultaneous failure of two of them can occur only as a coincidence and not as a result of failure of the first engine. As a result, adoption of the design features needed to ensure mutual functioning independence of the individual engines and their systems during the design of the airplane, followed by comprehensive practical verification of the effectiveness of these measures during ground (including static) and flight tests, are mandatory elements in the process in which a modern multiengined aircraft is developed.

For each aircraft, it is possible to establish an angle of attack (which, generally speaking, varies along the takeoff run) at which, in a given state of the surface, i.e., at a given value of the friction coefficient f between the tires and the surface, the total drag during the takeoff run will be minimized. This total drag is made up of two basic components: aerodynamic drag and the frictional drag of the tires against the surface.* The thrust margin $\Delta P = P - Q - f(G - V)$ is found to be largest when the takeoff run is executed at a certain optimum angle of attack and, consequently, the run is shortest in this case.

Existing aerodynamic-calculation techniques permit sufficiently accurate determination of this optimum angle of attack and its optimum variation during the takeoff run for each airplane and each state of the surface. However, it is found when such a calculation has been performed that any practically possible deviation from the optimum angle of attack (i.e., by $\pm 2°-3°$) has almost no effect on the takeoff-run characteristics.

This is because the aerodynamic drag of the airplane is found to be somewhat higher than the minimum possible if the takeoff run is executed at an angle of attack larger than the optimum, but, on the other hand, the force of friction between the tires and the surface is simultaneously reduced, since this force (like any other frictional force) is directly dependent on the normal force pressing the wheels against the ground. The normal force, on the other hand, decreases with increasing angle of attack because most of the airplane's weight is offset by the lift of the wing and is not transmitted to the landing-gear wheels. /149

The picture is reversed for a takeoff run executed at an angle of attack smaller than the optimum. The aerodynamic drag decreases as compared with the above case, but there is a corresponding increase in wheel friction because the wheels must carry a correspondingly larger fraction of the airplane's weight.

It is found as a result that the changes in the aerodynamic-drag forces and the forces of friction between the tires and the surface compensate (or, more precisely, almost compensate) one another in a rather broad range of takeoff-run angles of attack, so that their sum changes very insignificantly.

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*It is assumed here that the runway surface is horizontal and, consequently, there is no need to take account of the work (positive or negative) required to change the airplane's potential energy during the takeoff run.

To the above we should add that only 15-20% of the total amount of energy expended during the airplane's takeoff run is required to overcome both of the above forces. The remaining 80-85% are used to overcome the inertia of the airplane, i.e., to accelerate it. If we picture a hypothetical airplane that could take off in airless space and in the absence of friction (i.e., in the absence of both wheel friction and aerodynamic drag), accelerating this airplane from zero to a speed equal to the liftoff speed of its real prototype would take only 4/5 of the energy actually expended in taking this prototype off under real conditions. Thus, even a certain imprecision in compensation of an increase in one of the forces impeding acceleration by a decrease in the other has, on the whole, an extremely small effect on the takeoff-run characteristics.

Probably the only exceptions are takeoffs from loose dirt strips or from deep snow, when the fraction of gear drag in the total balance of forces acting on the airplane increases sharply and makes a takeoff run at a relatively large angle of attack ("with the tail half down") much more advantageous than one at the optimum angle, not to mention a still smaller one. However, modern multiengined aircraft seldom take off from such surfaces, and this is why these cases must be regarded only as exceptions.

In the overwhelming majority of cases, therefore, the takeoff distance does not depend very strongly on the angle of attack at which the run is made. However, the angle at which the airplane lifts off the ground is by no means a matter of indifference. Other conditions the same, the liftoff speed and hence also the takeoff distance depend precisely on the takeoff angle of attack. /150

To take off in the normal distance, the pilot must have established the predetermined angle of attack by the time of liftoff. *On the other hand, the manner in which this attitude is* reached from the initial parking attitude during the takeoff run is determined in practice not so much by the established optimum angle of attack as by the limitations applicable to the speed at which the landing-gear nose wheel can be in contact with the runway or, in the absence of such limitations, by considerations affecting the simplicity and convenience of piloting, and in particular by the amount of directional controllability retained by the airplane on failure of a side engine during the takeoff run.

In all cases, the initial stage of the takeoff run is executed in the parking attitude of the airplane, i.e., with the airplane resting on all landing-gear struts, since low-speed longitudinal controllability is not sufficient for changes in the pitch-angle attitude of the airplane. This makes it possible to hold to a straight-line takeoff run while the rudder is still ineffective by steering the nose wheel or jabbing at the main-wheel brakes.

After the speed at which the elevator becomes effective has been reached, the pilot can lift the nose of the airplane to the attitude corresponding to the chosen angle of attack and complete the takeoff run on the main wheels with the nose lifted.

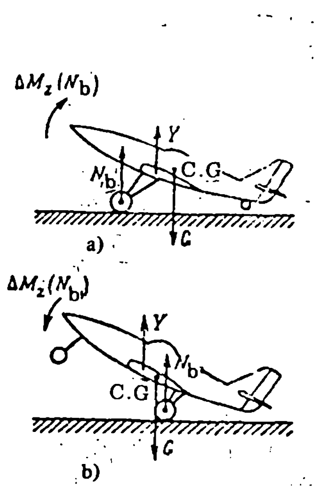

Figure 74. Longitudinal Stability During Motion Along the Ground on the Main Wheels. a) Airplane with tail wheels; b) airplane with nose wheel (with "tricycle" landing gear).

However, analysis shows that the longitudinal stability of an airplane with nose wheel is lower in motion along the ground on the main wheels than that of an airplane with a tail wheel. Maintenance of a constant pitch angle therefore requires more attention and more frequent intervention in control on the part of the pilot in the former case than in taking off an airplane of the old "two-wheel" type with its tail up. This is perhaps the only piloting element in which the tricycle gear compares unfavorably with the tail-wheel gear.

Figure 24 shows two aircraft that are completely identical in dimensions, weight, external outlines, stability characteristics, and all other mechanical and aerodynamic parameters, except for landing-gear design: one has a nose wheel and the other a tail wheel. As is seen from the figure, the normal ground reaction force applied to the main wheels will generate a stabilizing moment that helps increase /151
longitudinal stability in the case of the tail-wheel airplane, but, on the other hand, a destabilizing moment detrimental to longitudinal stability in the case of the nose-wheel airplane.

To verify this it is sufficient to imagine that the angles of attack of both of these airplanes have changed in the same direction, say in the direction of an increase, for some random reason. This results in an increase in lift. The fraction of the weight on the wheels and, consequently, the normal ground-reaction forces decrease accordingly, and, consequently, the moments generated by these forces about the center of gravity also decrease. But in the case of the tail-wheel gear, the moment tends to pitch the airplane up and its decrease will tend to reduce the angle of attack, i.e., to return the airplane to its original attitude. In the case of the tricycle gear, on the other hand, the moment of the normal ground reaction forces about the center of gravity acts in the pitchdown direction, and its decrease causes a still greater increase in the angle of attack, i.e., it aggravates the original random deviation.

The above does not, of course, imply that all airplanes with tricycle gear are longitudinally unstable during the takeoff run with the nose wheel lifted. The moment from the landing gear is not the only longitudinal moment acting on the airplane during the takeoff run. There are also moments from the wings, fuselage, powerplant thrust, and, most importantly, the tail, the interaction of which is what determines the sign and degree of the airplane's stability as a whole:

$$\sum M_z^\alpha = M_{z\,\mathrm{wg}}^\alpha + M_{z\,\mathrm{h.t}}^\alpha + M_{zP}^\alpha + M_{z\mathrm{g}}^\alpha + \cdots$$

However, other conditions the same, an airplane with tricycle landing gear actually does have a much lower degree of longitudinal stability during a takeoff run on its main wheels than an airplane that is similar to it in all other respects but has tail-wheel gear because we invariably have $M_{zg}^{\alpha} > 0$ in the former case and $M_{zg}^{\alpha} < 0$ in the latter.

The effort to relieve the pilot of the extra work and attention required to hold a tricycle-geared airplane at a certain definite pitch angle during the takeoff run was one of the factors leading to the appearance and extensive use of a new piloting technique during takeoff. In this technique, the pilot executes most of the takeoff run in the parking attitude (on all landing-gear struts) and lifts the airplane to the takeoff angle of attack with a smooth steady motion only when the liftoff speed is being approached, thus forcibly lifting it off the ground. /152

This piloting technique enables the pilot to divide his attention only between the airplane's direction of motion along the runway and the performance of the powerplant during the takeoff run, thus ensuring better performance of these two extremely important piloting elements and, at the same time, requiring less expenditure of neuropsychic energy by the pilot.

In addition, this takeoff technique ensures better controllability in the event of failure of an engine outside the airplane's plane of symmetry during the takeoff run: the pilot can keep the machine from yawing not only by using the rudder, but also by fanning the wheel brakes on the side opposite the inoperative engine, as well as by employing the most effective means for directional control on the ground – the steerable nose truck of the landing gear.

For these reasons, this piloting technique is now quite common, and is employed on most modern aircraft, both single-engined and multiengined. In some flight manuals, this method is the only one authorized. Thus, the "An-12 Crew's Manual" (1965) states that "...safety in takeoff requires that the takeoff run be made on all wheels." And the takeoff position recommended for the elevator trim tab of the Tu-104 airplane was even chosen so as to ensure a certain compression of the nose wheel against the runway surface during the takeoff run – an amount acceptable from the standpoint of strut strength, but still sufficient to give a marked increase in its effectiveness as a means of directional control. This last is especially important in the event of a continued takeoff following failure of one of the engines.

2. ABORTED-TAKEOFF DISTANCE. DISTANCE OF CONTINUED TAKEOFF WITH PARTIAL AND UNBALANCED THRUST. CRITICAL TAKEOFF-RUN SPEEDS (FIRST AND SECOND)

The relation between the distance that has been covered by the airplane (or by any other moving body) and the speed that it has developed is expressed for a given positive or negative acceleration by the formula /153

$$L=\frac{1}{2}\int_{V_1^2}^{V_2^2}\frac{dV^2}{j}, \tag{11}$$

where V_1 is the initial velocity of the motion (in a normal landing, $V_1 = V_{ldg}$; in an aborted takeoff V_1 is the speed at which the thrust of the running engines is cut and deceleration is started); j is the acceleration in the motion along the ground (in the case of deceleration, the acceleration is negative, $j < 0$); V_2 is the final velocity of the motion (for deceleration to a full stop, $V_2 = 0$).

The limits of integration in the formula correspond to the initial and final velocity values on the segment of interest to us. In accelerated motion, i.e., with a positive value of the acceleration j, the initial velocity is smaller than the final velocity. In the opposite case, when the motion is decelerated, the initial velocity value is larger than the final value.

The negative acceleration during rollout along the ground is

$$j=-\frac{g}{G}(Q+F),$$

where Q is the airplane's aerodynamic drag (including the drag of turboprop-engine propellers or reverse thrust, if used on the particular airplane, and also the drag of drag parachutes if they are used during the rollout under normal or emergency conditions); F is the friction of the landing-gear wheels, which equals f(G-Y).

It follows from (11) that the rollout distance after abortion of a takeoff depends strongly on the speed that has been built up. At a certain time during the takeoff run, speed generally reaches a value (we shall call it the critical value) at which a distance equal to the remaining available runway length (which consists of the runway proper and the clear zone) is required to lose the accumulated speed. Aborting a takeoff at a speed above critical will result in the airplane's running out of available runway.

From the flight-safety viewpoint, special interest attaches to the case in which the critical speed would be identical to the liftoff speed. This would mean that the takeoff could be aborted safely at any stage during the takeoff run, right up to liftoff. However, satisfaction of this requirement would require extremely long runways.* Moreover, as will be shown below, the necessary degree of takeoff safety can be provided in other ways without meeting the above extreme requirement. /154

On the takeoff run, whose length can be computed by the same formula, the acceleration is, in contrast to the rollout case, positive, and quantitatively equal to

$$j=\frac{g}{G}[P-Q-f(G-Y)],$$

while the limits of integration in the case of a normal takeoff are respectively $V_1 = 0$ and $V_2 = V_{1/o}$.

If, however, one of the engines fails during the takeoff run and takeoff is not aborted, but continued, the takeoff run will naturally be longer; it can be calculated as the sum of the lengths of two segments:

$$L_{contd} = L_1 + L_2.$$

The normal acceleration, which provides the full thrust margin $\Delta P = P - Q - f(G - Y)$, prevails on the first of these segments, while the second segment is characterized by a lower acceleration corresponding to partial thrust and, in some cases (for example,

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*In the general case, the relation $V_{cr} > V_{1/o}$ might also prevail; takeoff could then be aborted successfully even after liftoff. However the principal implication of this would be that the airplane is being operated on an airport too large for it.

with a windmilling turboprop propeller), an increased drag Q. The limits of integration on the first segment correspond to zero velocity and the velocity at which one engine failed:

$$V_1 = 0; \; V_2 = V_{fail};$$

and those on the second segment to the speed at failure and liftoff speed:

$$V_1 = V_{fail}; \; V_2 = V_{l/o}.$$

As the above formulas show, the basic quantities determining takeoff-run distance are the liftoff speed $V_{l/o}$ and the thrust margin ΔP on the takeoff run.

The liftoff speed in a partial-thrust takeoff is practically the same as its normal value (disregarding the comparatively small effect of the change in the vertical thrust component and the influence of the change in swept wing area on propeller-driven aircraft). On the other hand, the takeoff-run thrust margin decreases extremely sharply after failure of one of the engines, with the /155 result that the acceleration is found to be substantially smaller than in a normal takeoff. The greater the fraction of the takeoff run covered with partial thrust, the greater, naturally, will be the increase in the distance travelled by the airplane on the ground before liftoff.

In the general case, there exists a speed at which engine failure will lengthen the run by just enough to place the point of liftoff near the end of the runway.* If the engine fails at a lower speed, the airplane will not be able to lift off the ground inside the airport. But in all cases of engine failure at speeds higher than that indicated, there will definitely be enough runway for a partial-thrust takeoff and the airplane will leave the ground before reaching the end of the runway.

If the value of this speed (which is also critical, although in a somewhat different sense than in the preceding case) equals the value of the liftoff speed, this means that the airplane will not be able to lift off before reaching the end of the runway, even if it encounters a failure of one of its engines during the very last stage in the takeoff run. If, on the other hand, the critical velocity (in the latter sense of the word) is zero, the airplane can take off even if the entire takeoff run is performed with one engine out. From the standpoint of flight safety, this capability would also be extremely attractive, but it would require a disproportionately long runway for most existing airplanes.

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*Naturally, liftoff exactly at the end of the runway cannot be regarded as acceptable in practice for safety reasons. It is therefore necessary to consider that liftoff has occurred "near" the end of the runway if the airplane is already in the air over the outer end of the runway and has succeeded in gaining a few (4-5) meters of altitude.

However, as we know, takeoff is not completed by liftoff from the ground, even if this occurs successfully within the limits of the runway. In addition to the ground segment of the takeoff, there is also a segment on which the aircraft is airborne. The total length of these two components – from the start of the takeoff run to attainment of a certain specified altitude (usually 10 meters) with simultaneous acceleration to a speed that ensures safe execution of the initial climb is called the takeoff distance.

It is necessary for an airplane, after leaving the ground with one engine out, to begin climbing at a trajectory inclination angle (or at a rate of climb) such that the maximum takeoff distance stated by the applicable standards will not be exceeded.

In certain cases, satisfaction of this requirement requires acceptance of a certain deterioration in normal takeoff characteristics even with the powerplant fully operative. In the final /156
analysis, this compromise proves advantageous. On the Tu-124 airplane, for example, a decrease in the takeoff flap deflection from $\delta_{f\ t/o} = 20°$ to $\delta_{f\ t/o} = 10°$ improved the characteristics of a continued takeoff with one engine running to a degree such that it was possible to increase the takeoff weight (and hence the payload) by two tons, although the normal-takeoff distance was lengthened by 150-200 m. It was also found advantageous to go from $\delta_{f\ t/o} = 25°$ to $\delta_{f\ t/o} = 15°$ for the An-10 airplane; this increased the rate of climb at safe continued-takeoff speed by approximately 1 m/sec. Naturally, this also increased liftoff speed (from the condition $V_{l/o} \geq 1.07V_{stall}$) and, consequently, the length of the takeoff run (by 9-10%). However, there was no change in required runway length, since this is determined primarily to support aborted and continued takeoffs in the event of engine failure.

It should be noted that the conditions minimizing takeoff distance and takeoff run need not coincide in principle. Thus, for example, a decrease in the takeoff flap deflection angle on certain types of aircraft, while it increases liftoff speed and, consequently, the ground distance for a continued takeoff, at the same time improves the after-takeoff climbing characteristics so greatly that the takeoff distance becomes, on the whole, shorter.

Generally speaking, it is impossible to find the optimum compromise solution (in the above example, to select the flap deflection angle) without considering the specific characteristics of the airport. If the latter has runways of limited length, but is located in open, flat, obstacle-free terrain, our first concern should obviously be to shorten the takeoff run as much as possible, without attaching special importance to the trajectory inclination angle and the rate of climb in the subsequent ascent. On the other hand, for takeoffs from an airport having a long runway but relatively high and close-in obstacles, it would be natural to proceed with emphasis on the greatest possible reduction of the takeoff distance.

In practice, the need to make this decision arises quite infrequently: operational history has shown that the latter case is much more common than the former. Hence the entire technique for performance of a continued takeoff, which is stated in detail for each type of airplane (flap deflection, liftoff speed, safe initial climbing speed, etc.) is, as a rule, subject to the condition that the takeoff distance be made as short as possible.

Accordingly, it is also customary to treat the critical continued-takeoff speed as the lowest speed at which failure of one engine leaves the airplane capable not only of lifting off while still on the runway and crossing the far end of the runway with several meters of altitude, but also of staying within the established takeoff distance $L_{t/o}$. /157

The increase in the aerial segment of $L_{t/o}$ in a continued takeoff as compared with a normal takeoff on full thrust can be estimated with accuracy sufficient for practical purposes by the formula

$$\Delta L = \left(\frac{1}{V_{y\,\mathrm{av\,f.t}}} - \frac{1}{V_{y\,\mathrm{av\,f.t}}} \right) 15V,$$

where V is the average forward speed on the segment from liftoff to the point at which an altitude of 15 m is reached (it is assumed that this speed is the same in takeoffs with full and partial thrust); $V_{y\ \mathrm{av\ f.t}}$ is the average rate of climb on this segment in a normal full-thrust takeoff; $V_{y\ \mathrm{av\ p.t}}$ is the average rate of climb on this segment in a partial-thrust takeoff.

Thus, the existence of, as it were, two different meanings of the term "critical takeoff speed" emerges from our examination of both aborted and continued takeoffs. One of them is the critical speed of continued takeoff, after attainment of which the takeoff can be continued in spite of failure of one of the engines, and the other is the critical speed for aborted takeoff, on attainment of which takeoff can be aborted safely.

In certain sources (see, for example, [19]), these characteristic speed values are called the first and second critical speeds, respectively, and the path segments covered by the airplane during the takeoff run from the starting point to the point at which these critical speeds are reached are known respectively as the first and second critical takeoff-run distances of the airplane.

Figure 75 presents schematic curves relating the takeoff-run speed to the distance covered by the airplane in the cases of aborted and continued takeoffs.

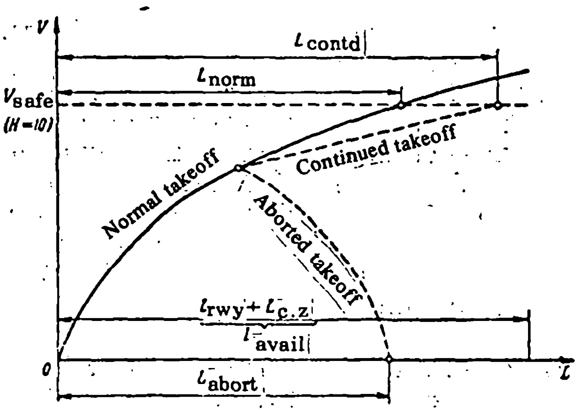


Figure 75. Variation of Speed V Over Distance L Covered in the Event of Engine Failure During the Takeoff Run, for Aborted and Continued Takeoffs.

The values of the first and second critical takeoff-run speeds usually lie somewhere between zero and liftoff speed, although, as we have noted, there are low-powered aircraft that are capable, when operated at large airports, of aborting takeoff even after they have left the ground – landing and completing their landing rolls within the available runway length. However, it is unnecessary to consider this case as in any degree characteristic.

If the two critical speeds are equal, the takeoff is said to be balanced. The distance required for safe execution of such a takeoff is accordingly also referred to as balanced. In this case, the critical speed, determined by the intersection of the curves L_{contd} and L_{abort} (Fig. 76) marks the boundary between the region in which the takeoff must be aborted (at $V_{fail} < V_{cr}$) /158
and the region in which it is equally obligatory to continue it (at $V_{fail} > V_{cr}$). The balanced-takeoff distance is of decisive importance in determining conformity of a certain specific airport to the requirements for operation of a given type of aircraft (at a given weight and under given weather conditions).

In practice, however, the balanced runway length may differ (more precisely, it almost always differs) from that actually available. If the actual length is greater than the balanced length ($L_{1\ avail} > L_{bal}$), then, as we see from Fig. 76, we obtain a certain range of speeds ΔV_1 within which the takeoff may be either aborted or continued, instead of a single speed value.

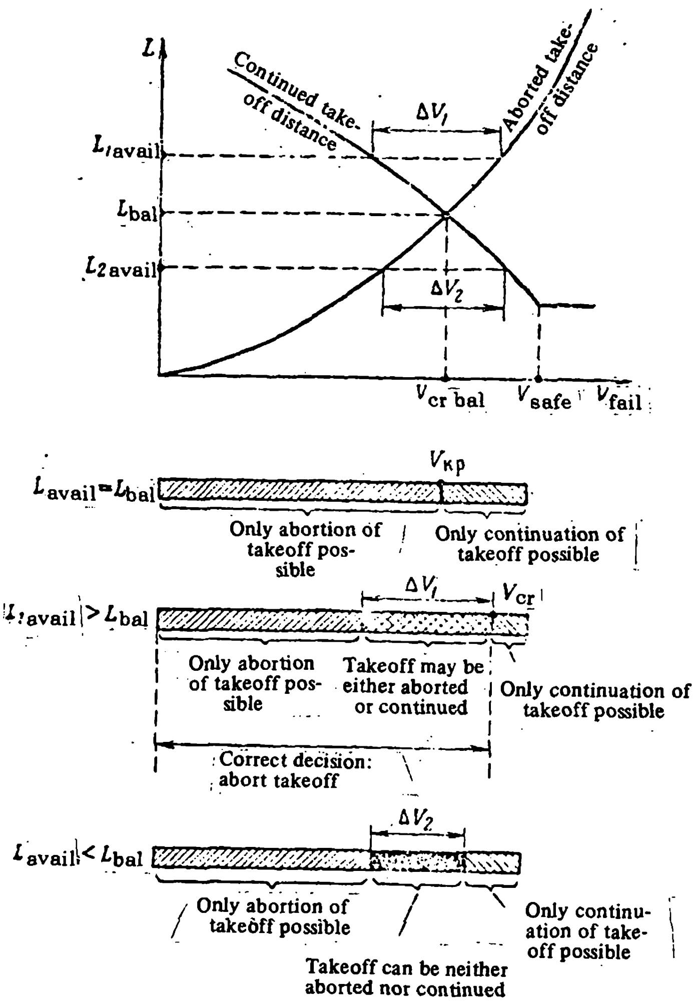

L
Continued take-off distance
Aborted take-off distance
ΔV1
L1avail
Lbal
L2avail
ΔV2
Vcr bal
Vsafe
Vfail
VKP
Lavail=Lbal
Only abortion of takeoff possible
Only continuation of takeoff possible
ΔV1
Vcr
L1avail > Lbal
Only abortion of takeoff possible
Takeoff may be either aborted or continued
Only continuation of takeoff possible
Correct decision: abort takeoff
ΔV2
Lavail < Lbal
Only abortion of takeoff possible
Only continuation of takeoff possible
Takeoff can be neither aborted nor continued

Figure 76. Illustrating the Concept of the Balanced Takeoff and Possible Deviations from it.

Needless to say, there is only one correct decision in the event of engine failure within this range, i.e., when a free choice is available: the takeoff must be aborted. In taking this position, we arrive at an unequivocal interpretation of the notion of the critical takeoff speed V_{cr} as the highest speed attained during takeoff at which, in the event of failure of the critical engine, it is feasible either to abort the takeoff within the limits of the available runway length or to continue it.

It is precisely this value that the pilot must be certain of in any takeoff (from a particular airport, under given weather conditions and at a given aircraft weight); the takeoff must be aborted in all cases of engine failure before this speed is reached and *continued* if the failure occurs *after* it is reached.

However, the very existence of the segment ΔV_1 indicates that there is a certain margin of runway length that may not be used in the event of engine failure during takeoff of an airplane of the particular type at a given weight and at given air-temperature and /159 -density values.

The situation is reversed if the actually available runway length is shorter than the balanced length ($L_{2\ avail} < L_{bal}$). Then the failure speed at which it is *just* possible to abort the takeoff is found to be lower than the speed at which it *first* becomes possible to continue it. In other words, a speed range /160 ΔV_2 emerges within which an engine failure would place the pilot in a highly critical situation: it would be equally impossible either to abort or to continue the takeoff. Needless to say, this situation is categorically unacceptable in the operation of passenger, sport-trainer, and other civil aircraft.

If it is found in computing the parameters of an upcoming takeoff that there is such a "desperation" segment on the takeoff run, the airplane's takeoff weight must be reduced to a figure such that the speed ranges in which the takeoff can be aborted and continued will at least be coterminous (at point V_{cr}) if not overlapping.

Here it is proposed that a "safe" outcome of an aborted takeoff be defined as a full stop within the limits of the available airstrip length L_{avail}, shich includes, in addition to the runway length L_{rwy}, also the length of the clear zone $L_{c.z}$. A "safe" continued takeoff presupposes liftoff within the limits of the runway at the normal speed established for the particular airplane and attainment of at least 4 meters of altitude at the end of the runway.

It must be stressed once again that the allowable takeoff weight and the critical takeoff-run speed must be calculated for the particular airport and a given set of specific atmospheric conditions. This is necessary because the critical takeoff-run speed does not depend on the properties of the aircraft alone. In addition to variations in actual takeoff weight, the length and condition of the airport surface (friction coefficient), the grade of the takeoff runway, air temperature, and wind speed and direction must be taken into account in determining these quantities. If even one of these conditions changes, the critical-speed computation must be corrected.

In computing the *continued-takeoff distance* with the critical engine out, it is customary to proceed from the practically realistic conditions of execution of such a takeoff, as regards both the time interval between the engine failure and the start of crew activity to compensate the loss of thrust (application of emergency power, manual control of propeller systems, etc.) and the values established for the altitude at which gear retraction begins and powerplant output parameters.

It should be noted that these time intervals (which are usually assumed equal to 3-5 sec) pertain only to intervention in control of the powerplant and auxiliary systems of the airplane. Control of the airplane's path, and directional control in particular, are, on the other hand, assumed to take place with the normal delay times characteristic for the pilot's reflex responses. Accordingly, the functions of counteracting the unbalanced-thrust moment after the nose wheel is lifted and holding the airplane on /161 the runway must be performed by deflecting the aerodynamic controls.

Arrival at the 10-meter altitude at the safety speed V_{safe} is followed by an initial climbing segment (to $H = 400$ m), the features of which will be set forth below, in Sec. 4 of this chapter.

3. RUDDER DEFLECTION ANGLE MARGIN IN TAKEOFF RUN AND AFTER LIFTOFF WITH UNBALANCED THRUST. INTENTIONAL UNBALANCING OF THRUST TO COUNTER THE INFLUENCE OF A CROSS WIND DURING THE TAKEOFF RUN

The thrust deficiency that arises on failure of one of the engines is not the only possible impediment to continuation of the takeoff. There is also the danger of deficient controllability in the directional plane — the lack of an adequate rudder-deflection margin. During the takeoff run, and especially on its first half, rudder effectiveness, which is proportional to the square of speed, is relatively low, especially on turbojet and turbofan aircraft, with which there is no propwash over the tail. On such aircraft, the critical engine is the one at the end of the longest arm from the airplane's plane of symmetry.

On propeller-driven (turboprop or piston) airplanes, identification of the critical engine also requires, as we have noted, consideration of the ground-loop moment from the propellers, which generally acts in the direction opposite to that of their rotation. Thus, for example, the critical engine of the Il-18 and An-10 aircraft is No. 4 (right outboard).

Cross winds also complicate piloting during an engine-out takeoff; here there is a least favorable combination of inoperative engine and cross-wind direction, e.g., failure of the critical No. 4 engine with a cross wind from the right on the Il-18 and An-10.

In many cases, therefore, the availability and amount of rudder-deflection margin in an unbalanced-thrust takeoff directly determine (along with the availability of reserve power) whether execution of such a takeoff will or will not be possible.

Banking the airplane toward the operative engines, discussed earlier as a highly effective means of reducing the required rudder deflection, is not applicable for an airplane in motion on the ground.

Among the other known means for directional control of an airplane in motion on the ground, the steerable nose wheel is best as regards both effectiveness and the absence of any detrimental effect on longitudinal acceleration. This device can be /162 used with equal effectiveness to counteract any external disturbance in the directional plane, i.e., not only unbalanced engine failure, but also cross winds and unequal friction coefficients at the main wheels (owing to surface nonuniformities, considerable differences in tire pressures, etc.).

Figure 77 shows a diagram of the controlling forces in a takeoff in a cross wind. We see from the figure that the lateral friction force $F_{n.w}$ of the nose wheel is directed in such a way that it produces almost no component along the airplane's longitudinal axis and, consequently, that the necessary moment in the directional plane is obtained with practically no detriment to the thrust margin and, consequently, to the airplane's takeoff properties.

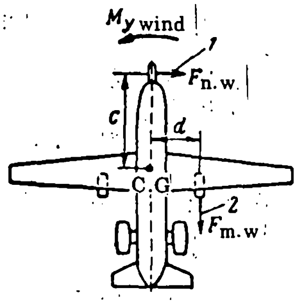


Figure 77. Diagram of Forces for Directional Control on the Ground. 1) Force applied to nose wheel; 2) braking force of main wheels.

In the event of failure of one of the engines on an airplane that does not have a steerable nose wheel, the basic remaining means of holding direction on the first half of the takeoff run, while the rudder is still ineffective, is to brake the main wheel (force $F_{m.w}$) on the side opposite the inoperative engine.

However, there are important drawbacks to this procedure. First, it sets up an additional resistance that further reduces the already lowered thrust margin. In addition, wheel braking is not effective in all cases: it cannot always keep the airplane from veering on a slippery (icy or wet) runway surface. Although it is true that the steering action of the nose wheel is also reduced somewhat in the latter case, it does not deteriorate as much as braking action does.

It should be noted that both the use of the nose wheel and the use of unsymmetrical braking require that the takeoff run be made on all landing-gear struts. In a takeoff run with the nose wheel lifted, braking is usually impossible or extremely difficult, since it generates a pitchdown moment that brings the nose wheel down so hard as to risk damage to it.

With respect to the magnitude of the steering moment that can be generated, the steerable nose wheel is considerably more effective than unsymmetrical wheel braking. Usually, turning the nose wheel through no more than half of its limiting angle produces a steering moment equal in magnitude to that generated by locking up one of the main landing-gear wheels.

Finally, note should be taken of the fact that use of the steerable nose wheel provides considerably higher precision in control of the airplane in motion along the ground, while main-wheel braking is inevitably uneven in nature. In this sense, controlling the airplane with the nose wheel can be likened as regards its smoothness to steering an automobile, while control by pulsed braking of the wheels is more like steering a caterpillar tractor. /163

In evaluating the above, it should be remembered that the problem of motion along the ground with unbalanced thrust generally never arises in practice at low speeds (i.e., in the initial stage of the takeoff run): we have shown that the only correct decision in any case of engine failure before attainment of the critical speed is to abort the takeoff run and, consequently, the subsequent motion along the ground will occur under nearly balanced thrust conditions, i.e., will not require the use of any special measures to maintain direction. On the other hand, in the event of engine failure after the critical speed has been reached, rudder effectiveness is usually sufficient to ensure straight-line motion on the rest of the run, and only in rare cases (for example, with a strong cross wind from the side of the inoperative engine) will it be necessary to apply a small additional moment, which can then be generated with the steerable nose wheel or by light braking of the wheels on one of the main landing-gear struts.

After lifting the airplane off the ground with unbalanced thrust, the pilot must be ready to counter a tendency to yaw, which becomes stronger again in spite of the continuing buildup of speed. This obscure effect, which has been almost totally neglected in the literature, often comes as a surprise to the pilot.

Figure 78 shows schematically the causes of this phenomenon. As long as the airplane was running along the ground, the lateral force arising as a result of the rudder deflection could not divert the airplane toward the inoperative engine to any perceptible degree, since it was offset by the lateral component of the friction of the wheels against the ground. With liftoff, however, the wheels lose contact with the ground, the friction effect

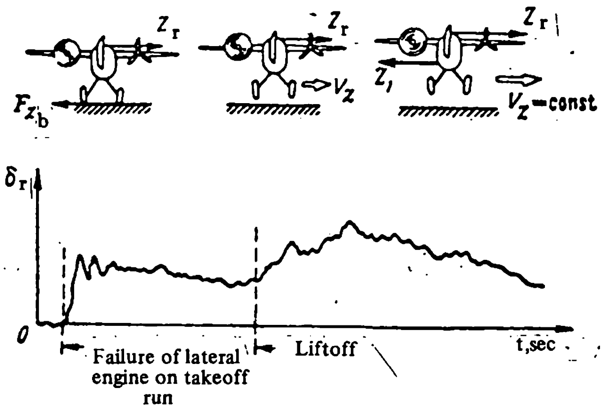


Figure 78. Illustrating Causes of Increased Yawing Tendency After Liftoff in an Unbalanced-Thrust Takeoff.

naturally disappears, and, under the action of the unbalanced lateral force, the airplane begins to slip in the direction of the inoperative engine in exactly the same way as in any other case of zero-roll unbalanced-thrust flight. The slip gives rise to a lateral aerodynamic force that is applied aft of the airplane's center of gravity and thus generates an additional moment acting in the same direction as the unbalanced-thrust moment. To offset this additional moment, it is necessary either to increase the rudder deflection or to bank the airplane a few degrees in the direction of the running engines.

/164

Unawareness of the described effect may place a pilot taking off with an inoperative lateral engine in a difficult position, and at precisely the moment at which it appeared to him that the adequacy of the rudder-deflection margin available for countering the unbalanced-thrust yaw had just been established beyond a doubt.

After liftoff from the ground, an airplane taking off with unbalanced thrust may in some cases also show a tendency to roll in addition to the above-described yawing tendency. The direction and rate of this roll depend chiefly on the relation between the two basic transverse moments acting on the airplane:

— the transverse static stability moment

$$M_x = m_x^\beta \beta q S l,$$

which tends to roll the airplane toward the running engines;

— the moment due to removal of the propwash over a certain segment of the wing behind the nonfunctioning engine. This moment, which naturally appears only on piston-engined or turboprop aircraft, tends to roll the airplane toward the inoperative engine.

Hence the rate and even the direction of the roll (the latter in the case of propeller-driven aircraft) are difficult to establish in advance in general form. They must be determined during the flight tests of the airplane. In all cases, the pilot must remember that a roll toward the inoperative engine is especially undesirable after liftoff (a slight roll in the direction of the running engines is, as we know, not only safe, but even desirable in the interests of counteracting slip). /165

In conclusion, we note that in an unbalanced-thrust takeoff, it is necessary to get the airplane off the ground cleanly, without allowing the wheels to touch the runway again, since, owing to the slip that develops in this case, such contacts occur with crabbing relative to the runway surface and, on the one hand, impose the corresponding loads on the landing gear and, on the other hand, give rise to additional rolling impulses toward the nonfunctioning engine.

In much the same way as in the landing approach, artificial application of unbalanced thrust may become inevitable in a cross-wind takeoff, even when the airplane's powerplant is fully operative.

With the universal conversion from dirt strips to concrete runways, as we noted above, the cross-wind takeoff has become common aviation practice, and is even more frequent than the takeoff in the plane of the wind.

The basic peculiarity of a piloting nature associated with the cross-wind takeoff consists in the appearance of a tendency of the airplane to yaw. Essentially, this tendency is a manifestation of an unquestionably positive property of the airplane: its directional stability. However, it is necessary to distinguish directional stability in motion along the ground from directional stability in flight. The values of these two characteristics may differ from one another, sometimes quite substantially, owing to the fact that the steering moments acting on the airplane as it moves along the ground include one that does not influence directional stability in flight: the moment from the lateral reaction forces of the wheels.

Older types of aircraft, which had tail-wheel landing gear, had a stronger tendency to yaw in cross winds than modern tricycle-geared aircraft precisely because the moment about the airplane's center of gravity from the wheel lateral reaction forces acted in the same direction as the static directional stability moment in the former case, while it acts in the opposite direction in the latter case.

On certain types of aircraft, such as freighters having special fuselage shapes with the tail section swept up at the bottom, the lateral aerodynamic force may even be applied at a point forward of the main wheels, with the result that when it takes off in a cross wind such an airplane, unlike most, will show a tendency to yaw not in the direction from which the wind is blowing, but in the opposite direction.

Like the countering of a thrust imbalance due to failure of one of the engines, cross winds are best handled during the takeoff run by means of a steerable nose-wheel truck. However, when the particular type of airplane does not have a steerable nose wheel and rudder deflection is not effective enough, especially during the first stage of the run, two other possibilities are left to the pilot: unbalanced braking of the main wheels and (on aircraft whose powerplants consist of two or more engines sufficiently far outside the plane of symmetry) an unbalanced adjustment of powerplant thrust. /166

It is not possible to answer the question as to which of these two procedures is most advantageous in the general case or applicable for any airplane and any set of takeoff-run conditions.

The relative offsets of the outboard engines and the main landing-gear wheels from the airplane's plane of symmetry constitute the basic factor determining the answer to this question in each specific case. To minimize the loss of takeoff performance (i.e., loss of takeoff-run acceleration), it is desirable to set up the steering moment necessary to counter the yaw with a minimal sacrifice of the thrust margin that provides this acceleration.

If the outboard engines are located farther from the plane of symmetry than the landing-gear wheels, the necessary steering moment can be obtained with a loss of thrust from the downwind outboard engine that is smaller than the friction between the braked wheel and the surface that would be necessary to develop the same moment (Fig. 79). Thus, for an airplane whose outboard engines are quite wide of its centerline, while its landing gear, on the other hand, has a comparatively narrow track, it is more advantageous to hold direction during takeoff by setting the outboard engine to takeoff power after the rest (if, we repeat, it is for some reason impossible to use the steerable nose-wheel truck).

On the other hand, for an airplane whose engines are quite close to the fuselage (e.g., the turbojet passenger aircraft of the "Tu" family), so that it is difficult to set up a sufficiently large steering moment even with a substantial reduction of the thrust from one of them, while its landing gear has a comparatively wide track, it is advantageous to hold direction at the start of takeoff in the same way as this is done on single-engined aircraft – by light braking of the main-gear wheels on the necessary side.

There are, admittedly, exceptions to this general rule of using the force acting at the end of the longest arm. Thus, in taking off from a slippery (e.g., icy or wet) runway surface, even wheels situated on a rather long arm may produce an inadequate /167 braking action. And in taking off from a surface having a nonuniform friction coefficient (for example, when icy patches alternate with clean concrete or snow), use of the wheel brakes may

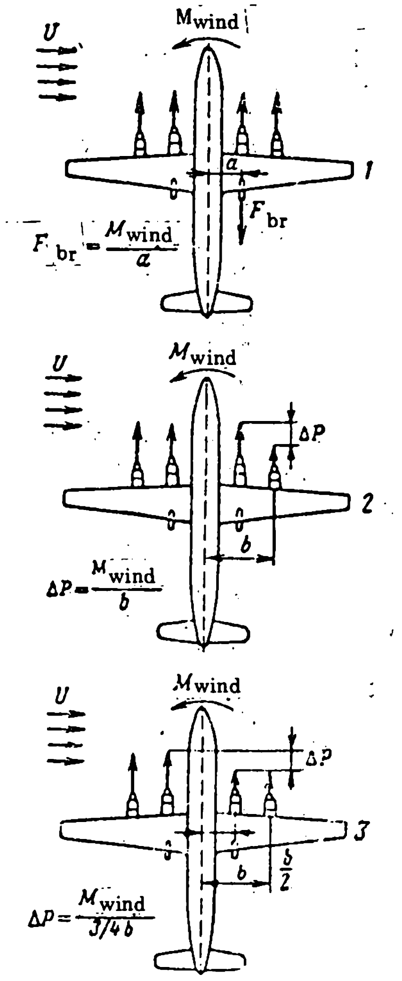

U
M_{wind}
a
1
F_{br}
$F_{br} = \frac{M_{wind}}{a}$
U
M_{wind}
ΔP
2
b
$\Delta P = \frac{M_{wind}}{b}$
U
M_{wind}
ΔP
3
b
$\frac{b}{2}$
$\Delta P = \frac{M_{wind}}{3/4 b}$

Figure 79. Obtaining Desired Steering Moment During Takeoff Run by Braking a Wheel and Cutting the Thrust of an Outboard Engine. 1) Wheel braking; 2) reduction of thrust of one (outboard) engine; 3) reduction of thrust of all engines on one side (M_{wind} is the yawing moment due to the cross wind; ΔP is the thrust imbalance; F_{br} is the braking force; a is the distance from the wheel plane to the airplane's plane of symmetry; b is the distance from the engine axis to the airplane's plane of symmetry).

produce sharp and sometimes even dangerous swerving of the airplane from side to side. In some cases, this makes it necessary to abandon the main-wheel brakes as a means of holding direction in the takeoff run even on aircraft on which it is generally advantageous from the standpoint of minimizing takeoff-performance losses.

On the other hand, in reducing the thrust of one of a set of gas-turbine engines to obtain directional control during the takeoff run, allowance must be made for the fact that these engines usually respond to the throttle much more sluggishly than piston engines, so that the quick thrust buildup that is possible on propeller-driven aircraft is by no means always obtainable on jets.

Thus, small deviations from the takeoff-run direction that require comparatively small directional impulses for their correction are sometimes better handled by cautions braking of the corresponding landing-gear wheel, even if it is on a shorter arm than the outboard engine.

However, the general conclusion drawn above stands in spite of these exceptions: if for any reason it is impossible to hold to the takeoff-run direction by using the basic /168
directional-control elements (the rudder and a steerable nosewheel truck), and it is necessary to use means that involve a longitudinal force in the direction opposite to the velocity, it is more advantageous to select from along them that with which this force acts on the longer arm.

4. INITIAL CLIMB. RETRACTION OF GEAR AND FLAPS AFTER TAKEOFF WITH PARTIAL AND UNBALANCED THRUST. ENGINE FAILURE AFTER LIFTOFF FROM THE GROUND

On the continued-takeoff distance, the airplane accelerates, lifts off the ground, and gains its first 10 meters of altitude simultaneously and with continuous acceleration, with the result that its speed when it reaches the ten-meter distance from the ground should have reached V_{safe}, which ensures safe continuation of the climb. After this point, all of the available power (excess power) of the operative part of the powerplant may be used for a certain time to increase only the potential component of the flying airplane's energy, i.e., in climbing. Naturally, the trajectory inclination angle is steeper here than during acquisition of the first 10 meters, when powerplant energy was being expended chiefly to increase the airplane's kinetic energy, i.e., for acceleration.

During the initial climb, the airplane must, while clearing obstacles near the airport, climb to several hundred meters above airport level (usually 400) and change from its takeoff to its flight configuration with retraction of the flaps and the corresponding increase in speed; thus it becomes fully prepared for accomplishment of the next stage of flight, that of steady climb to the assigned altitude.

The change from takeoff to flight configuration consists of two basic elements: retraction of the gear and resetting of the flaps from their takeoff to their cruising (i.e., usually retracted) position.

Generally speaking, it is advisable to retract the gear as soon as possible after continuing a takeoff with partial and unbalanced thrust – if possible, immediately after clean separation from the ground, when the possibility of another contact between the wheels and the runway is definitely excluded, i.e., at a height of 3-5 meters.

The reason for this recommendation is obvious: the sooner the gear is retracted, the more quickly will the airplane be free of a certain fraction of its aerodynamic drag; this is equivalent to increasing the thrust margin, as is so necessary in such a situation.

However, there are also exceptions to this general rule. In particular, the landing-gear aerodynamic drag of certain types of aircraft is higher during retraction or lowering than when the gear is all the way down. This is the case when the wheel or the entire truck is rotated relative to the free airstream during retraction in such a way that the flow is disturbed to a still greater degree than it was before gear retraction began. A similar effect may sometimes be produced when doors that cover the /169 landing-gear wells when the gear is either down or retracted open up during the actual retraction or lowering to let the struts with the wheels into or out of the well.

In all such cases, the flight-performance data of an aircraft taking off with partial thrust (rate of climb, forward acceleration, etc.) may prove to be even worse during gear retraction than in flight with the gear down. By way of example, we might cite the Tu-104 airplane, whose rate of climb averages 0.5-0.6 m/sec lower in the interval between the tenth and thirty-fifth to fortieth seconds of the gear-retraction period of a takeoff on one engine than when the same takeoff is made with the gear fully lowered [14].

In such cases, the gear should not be retracted immediately after liftoff, but delayed until obstacles at the edge of the airport have been cleared and the airplane has built up sufficient speed.

Retraction of the flaps also reduces aerodynamic drag, but it lowers lift simultaneously. For this reason, great caution should be exercised in retracting the flaps in the interest of improving partial-thrust takeoff characteristics.

The flaps of certain types of aircraft retract rather rapidly, causing the airplane to "settle," i.e., to experience a temporary decrease in rate of climb or even to descend slightly. On such aircraft, and especially in takeoffs with partial and unbalanced thrust, the flaps should be retracted in strict observance of the minimum permissible altitude values established from flight-test data (100 meters, etc.). Another effective way to counteract the "settle" is to "jog" the flaps up – to retract them in several increments separated by time intervals. In all cases, even a temporary loss of altitude during a takeoff with partly inoperative powerplant must be prevented at all costs: at no point should the path inclination angle be allowed to assume a negative value.

As we pointed out above, the normal takeoff deflection of the flaps is sometimes deliberately set below optimum in order to make a continued one-engine-out takeoff easier. The trajectory characteristics of an airplane are below maximum to some degree in any normal takeoff, but there is a compensating higher degree of safety in the design case – that of a continued takeoff after failure of the critical engine. As a result, it is sometimes even found possible to increase the airplane's takeoff weight, which is frequently limited by precisely this design case. /170

For aircraft that do not settle on retraction of the flaps, there is no fundamental reason for limiting the minimum allowable altitude for performance of this operation. Nevertheless, such limitations are imposed to minimize the distraction of the pilot's attention by any secondary operations at low altitude, especially in the execution of a maneuver as complex as a continued takeoff with one engine out.

While retracting the gear and flaps, the pilot must continue attentive monitoring of the other elements of his task – countering the tendencies to roll and yaw and also watching flight speed carefully, since a speed loss during a takeoff with partial and unbalanced thrust is particularly dangerous and at the same time more probable than in a takeoff with a fully operative powerplant.

Clearance of obstacles after a takeoff with partial and unbalanced thrust (and, incidentally, after a normal takeoff) requires first of all that the airplane reach not its highest possible rate of climb V_y, but the largest possible climbing-path angle θ (with observance, of course, of the condition $V \geq V_{safe}$).

The climbing angle will be substantially smaller than normal in a partial-thrust takeoff. It is necessary to remember this and, in order to prevent dangerous loss of speed, never to attempt to bring the airplane to the normal climbing angle to which the pilot is accustomed by increasing its pitch angle.

The above also applies in full measure to takeoffs with the powerplant fully operative, in which extreme climbing angles should also be avoided because an engine failure occurring in the initial-climb stage at a large pitch angle causes an especially sharp drop in speed, and perhaps a total speed loss and a stall from which it will be practically impossible to recover in the absence of an altitude margin.

It is, of course, possible (and necessary) to counteract a loss of speed with an immediate reduction of the climbing angle when the very first signs of engine failure are detected. However, this action, even when carried out with commendable crispness, is not fully effective at all initial climbing angles.

V.F. Bolotnikov [1] pointed out that there is a certain range of climbing conditions within which even instantaneous, zero-delay pilot actions do not necessarily prevent loss of speed. /171

The physical reason for the existence of such critical climbing-angle values is that, like any other body possessing a certain mass, an airplane gaining altitude at a certain rate of climb cannot be transferred instantly to some other flight regime in which a different vertical velocity prevails.

Immediately after the drop in thrust, as is shown schematically in Fig. 80, the airplane will move along a certain curved path while continuing to climb (although with a rapid decay of its vertical velocity) and, consequently, will simultaneously lose speed. The example presented here pertains to a single-engined airplane,

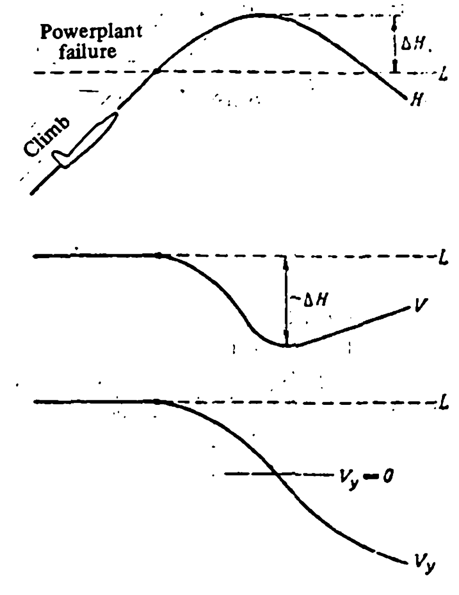


Figure 80. Motion of Airplane After Engine Failure During Climb.

i.e., to the case of total thrust loss on engine failure during the climb. However, even with a partial powerplant failure and the corresponding decrease rather than total disappearance of thrust, the new steady-climb vertical velocity, even if it remains positive, is naturally much smaller in absolute magnitude. The airplane cannot change instantly to this new value of V_y. Hence the conclusions drawn above remain in force for our case as well.

The only guarantees against emergence of this dangerous situation are margins in both speed and climbing angle and, of course, quick and sure responses from the pilot, who, upon failure of the engine, drops the airplane sharply (under a g-force much smaller than unity) into a new attitude corresponding to steady flight at the new lower thrust value.

Generally speaking, the above applies for aircraft climbing at any altitude, but it is especially important at takeoff, both because of the special hazard presented by loss of speed and stalling near the ground and because the low-speed climb at large path /172
inclination angles is practically never used in other flight cases.

A word of caution is in order regarding the recently noted foreign practice of flying the climb immediately after takeoff at unusually large path inclination angles and, accordingly, at large pitch angles. The primary motive behind this piloting maneuver has been the effort to gain considerable altitude while the airplane is still in the zone immediately adjacent to the airport in order to reduce noise when it flies over populated areas farther ahead on its path. This is one of the most serious problems in flight operations with modern aircraft. To appreciate the importance attached to it, it is sufficient to recall that in many cases recourse has been taken to a measure as extraordinary as performing the initial climb at partial powerplant thrust with the object of reducing noise.

The noise from the aircraft decreases substantially with increasing altitude above the ground and a steep climb at takeoff has certain advantages from this point of view. In considering this problem, however, we may not overlook the fact that, as we have shown, the range of possibilities for counteracting the dangerous consequences of a possible failure of one engine is greatly narrowed in this case. We cannot exclude the possibility that some of the crashes on takeoff that have been reported in the press (for example, the 1962 crash of the American Boeing 707 at Paris) might not have occurred if the climb had been flown at a shallower angle.

5. THE SPECIAL CASE OF ENGINE FAILURE ON TAKEOFF IN THE RANGE OF FLIGHT CONDITION TWO

We showed above that a range of speeds within which the thrust required for level flight exceeds the available thrust and, consequently, level flight is impossible even though the airplane could fly without losing altitude at the same weight, in the same configuration, and with the same thrust at slightly higher speeds may exist in the range of flight condition two.

In the takeoff configuration of the airplane – gear and flaps down – the existence of this danger zone is even more probable than in the flight configuration.

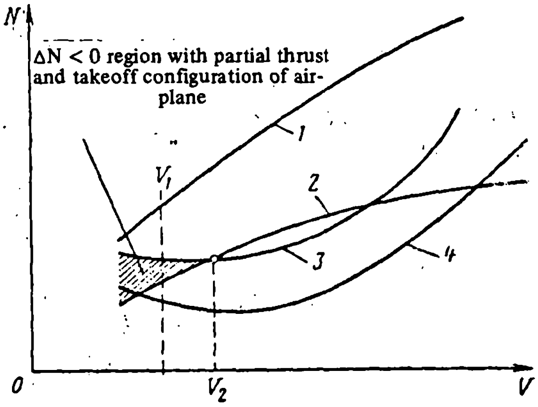


Figure 81. Special Case of Engine Failure on Takeoff. 1) N_{avail} at full thrust; 2) N_{avail} at partial thrust; 3) N_{req} in takeoff configuration; 4) N_{req} in flight configuration. /173

Let us suppose that a partial powerplant failure has occurred during takeoff at the time at which the airplane was moving at speed V_1 (Fig. 81). The power margin is negative at this speed and, consequently, the airplane cannot accelerate further. If the pilot has no way of increasing his power margin quickly (for example, by augmenting the thrust of the remaining running engines or by retracting the gear quickly), there is nothing to do in this situation but put the airplane down – more precisely, to let it put itself down – in a straight-ahead landing. With all the risks that such a landing presents, it is still less dangerous than an attempt to force the airplane to stay in the air, which would be inconsistent with the laws of flight mechanics and would have no outcome other than a total loss of speed and a stall.

Nevertheless, there is reason to assume that the probability of the attempt – even on the part of a comparatively experienced pilot – to make the airplane fly when it cannot fly cannot be excluded in this case in spite of its hopelessness. The first reason for this is that, as we have shown above, quick detection of the very fact that one of the engines has failed, especially on aircraft of modern configuration, is at times difficult. Not suspecting engine failure, the pilot may attribute the airplane's evident sluggish acceleration and even a descent to some random external cause that will go away of itself in a few seconds.

The second and, obviously, the most important reason is that even when he has detected an engine failure, the pilot still expects the airplane to continue accelerating, if not as rapidly, /174 because he definitely knows that an airplane of the particular type can fly level on the rest of its engines and in the given configuration. He is inclined to interpret the loss of acceleration to the fact that the actual climbing angle is large for partial-thrust flight. Acting on this hypothesis, he reduces the climbing angle or even puts the airplane into level flight, still unaware that the only alternative remaining to him is to land the airplane straight ahead at once. As a result, the airplane quickly loses speed (because, as we know, deceleration takes place more rapidly in the condition-two range) and stalls unless by this time the ground is directly underneath its wheels.

There is only one way to be sure of eliminating the possibility of such a situation: to make it impossible to continue takeoff when the airplane enters the range $\Delta N < 0$ shown in Fig. 81. Essentially, this requirement is equivalent to a mandatory abort of the takeoff if an engine fails at a speed below critical (the critical speed must, by definition, ensure safe continuation of all flight stages after engine failure).

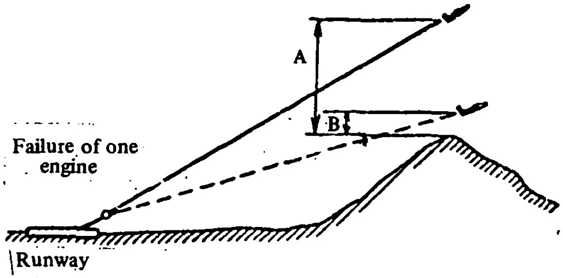
However, if the pilot of a modern airplane somehow encounters failures of more than one engine on takeoff (this nondesign case might occur, for example, in flight testing, when the equipment has not yet been brought up to the necessary reliability level) and finds that the airplane will no longer accelerate or, even worse, loses the speed that it had built up, there is no point in continuing to hold the airplane up and attempting to avoid a forced straight-ahead landing.

6. CLIMB WITH PARTIAL AND UNBALANCED THRUST TO THE FIRST TURN

On completing the initial climb, the airplane continues to ascend in its flight configuration at normal speed. In many cases, the time for which is it permissible to run the operative engines at takeoff power elapses at about this time, so that the problem of optimum utilization of available power output again becomes acute.

In particular, the advantages of zero-slip flight with roll toward the running engines, which permit however insignificant an increase in the rate of climb as compared with a straight-line slipping climb without roll, become especially important.

If the climb is being flown under difficult weather conditions with the ground obscured, it must be remembered that obstacles that would normally be quite far from the airplane's path may be dangerously close to it both vertically and horizontally in a climb with partial thrust. The height coordinate requires no special explanation. Obviously, if the airplane takes off in the direction toward an elevation, the height at which it is cleared at the lower rate of climb and, consequently, the flatter-than-normal trajectory, will be considerably smaller than usual (Fig. 82); this is taken into account in all applicable standards for evaluating an airplane's capability to continue takeoffs.



/175

Figure 82. Climb-Path Profiles of Aircraft with Full and Partial Thrust Relative to Ground Obstacle: A) Clearance of obstacle in normal takeoff; B) clearance of obstacle in partial-thrust takeoff.

However, it is also found necessary in such cases to consider ground obstacles to either side of the assigned track. In fact, as we pointed out in Chapter III, the slip in unbalanced-thrust zero-roll flight also influences the navigation elements: the airplane "crabs" toward the inoperative engine just as it would in the presence of a cross wind. Here the actual track of the airplane will differ from that computed before takeoff with consideration of the expected wind force and direction. If there are obstacles like those shown schematically in Fig. 83 near the assigned track line, the difference between the actual and computed track angles may result in a dangerously close approach to them, especially under the conditions of instrument flight in clouds or at night.

The danger of such crabbing is eliminated by recourse to the universal countermeasure against slip that we have referred to several times above: rolling the airplane 2-4° toward the running engines. Thus, roll is advisable here for two reasons: To obtain the highest possible rate of climb V_y and to counteract crabbing away from the track line. /176

7. INTENTIONAL TAKEOFF WITH PARTIAL AND UNBALANCED THRUST

We noted above that, as a rule, takeoffs with partial and unbalanced thrust can occur only in the event of unexpected engine failure at a stage during the takeoff at which the takeoff can no

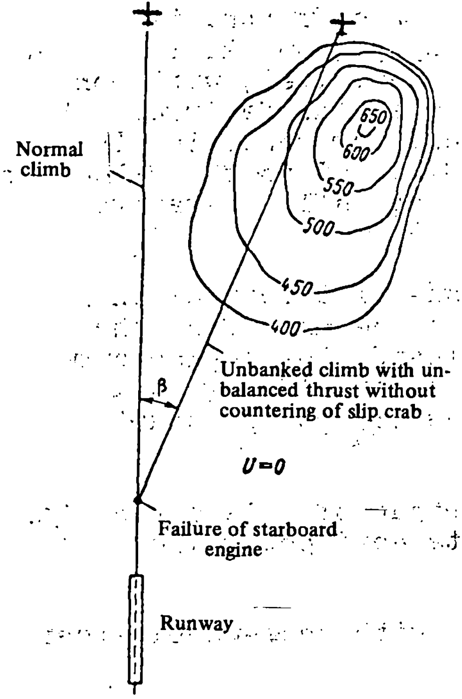

Normal climb
650
600
550
500
450
400
Unbanked climb with unbalanced thrust without countering of slip crab
β
U=0
Failure of starboard engine
Runway

Figure 83. Climbing Trajectories of Aircraft with Balanced and Unbalanced Thrust Near Obstacles in Plan View.

longer be aborted. However, there may be exceptional circumstances that require execution of a takeoff when it is definitely known that one of the airplane's engines will not be running. They arise, for example, when serious engine trouble excluding the use of the engine during takeoff is detected in a ground inspection far from the airplane's home base. If the engine cannot be repaired on the spot, the only solution is to take off and return home with fewer than all of the engines running.

Some flight units have experience in ferrying aircraft in this condition. Needless to say, ferrying is the sole concern in such cases; it may not be combined with any other mission, not to mention the transport of passengers.

Material on techniques for such ferrying flights will be found in the technical literature. Thus, for example, Engineer-Pilot P. Khmel'nitskiy and Engineer D. Levin, working from available practical experience in ferrying of Il-18 airplanes with three engines running [18], report that the flight can be made without removing the propeller from the /177 inoperative engine, but only if it is feathered and locked. However, a feathered and locked propeller begins to rotate in flight at speeds above 350 km/h, with a resulting increase in aerodynamic drag. It is therefore recommended that, instead of feathering the propeller, all of its blades be dismounted. It is also advisable to cover the air intake to prevent the oncoming airflow from spinning the engine's compressor.

In making preparations for such a flight, it must be remembered that the airplane is, as it were, transformed from a four-engined to a three-engined type at the very outset, so that the possibility of an unintended failure of at least one more engine during the actual flight must be reckoned with. It is necessary to form a clear plan of action (change in altitude, route, etc.) in advance for this eventuality, so that the situation will not be altogether unexpected. In particular, flight over mountainous terrain and large bodies of water should be avoided.

The design of the takeoff — in particular, calculation of the takeoff weight and the corresponding takeoff-run, takeoff, and aborted-takeoff distances, critical speed, and liftoff speed— should be approached in exactly the same way, i.e., with consideration of the possibility of one more engine failure. The authors recommend a simple rough procedure for computing the takeoff-run and takeoff distances by adding 25% to the values corresponding to a takeoff with the powerplant fully operative and all other conditions unchanged.

It is recommended that the total takeoff thrust of only the two symmetrically opposite running engines be used from the very start of the takeoff run. On the other hand, the engine symmetrically opposite to the inoperative one should have a low setting (20° on the throttle-position indicator) at the start of the takeoff run.

As the airplane gains speed, the output of this engine is gradually increased so that it reaches takeoff power when the speed reaches 200-210 km/h.

The entire takeoff run is performed with nose-wheel steering operative.

These recommendations, which were submitted for application to the Il-18 airplane, can also be extended to other types. On aircraft with engines less widely spaced along the span than those of the Il-18, the takeoff can be executed with all three running engines at takeoff power either from the very start of the run or from some very early stage in it. In practice, the directional-control means available on modern aircraft — the nose wheel and the rudder — are fully adequate to hold the airplane in a straight line on an unbalanced-thrust takeoff run.

Chapter VI /178

GENERAL REQUIREMENTS AS TO FLIGHT CHARACTERISTICS OF CIVIL AIRCRAFT WITH PARTIAL AND UNBALANCED THRUST

1. PRINCIPAL POINTS OF AIRWORTHINESS STANDARDS REGULATING THE BEHAVIOR OF AIRCRAFT AFTER PARTIAL POWERPLANT FAILURES

The aircraft airworthiness standards adopted by the International Civil Aviation Organization (ICAO) devote considerable space to the behavior characteristics of aircraft on engine failure and during subsequent flight with partial and unbalanced thrust. Besides these standards (the "International Standards"), individual countries with civil-aviation industries apply their own airworthiness standards ("National Standards"), in which the corresponding requirements made of the aircraft are set forth in more complete and detailed form.

It must be demonstrated regarding aircraft of ICAO member nations, and aircraft operated on international routes (irrespective of whether or not the nation to which they belong is an ICAO member), that if they conform to the National Standards of the country in which they were built, these standards are adequate to conform to ICAO requirements.

It is not our object in the present chapter to review the content of applicable airworthiness standards for aircraft. The sole intent of the few examples given below is to point up the nature of these standards, which do not lay down any specific design solutions or piloting techniques, but deal with the properties that a passenger aircraft must have to ensure adequate flight safety, in particular with partial and unbalanced thrust.

One of the crucial points in these standards that is especially important in the so-called "special cases of flight," which include flight with partial and unbalanced thrust, is the requirement that "attainment of the flight characteristics established for the airplane not require exceptional skill or excessively strained attention on the part of the pilot" ([23], Par. 2.2.1.2).* /179

Essentially the same requirement is repeated specifically later on in application to the unbalanced-thrust case: "...changes in power output shall not require exceptional piloting technique, strained attention, or excessive effort from the pilot, even in the case of failure of any engine in operation" ("Controllability" section, Par. 2.3.1); "...the airplane must have a degree of balance...such that the attention requirements made of the crew in performance of a flight and the conditions for holding to the required regime will not be excessive... This shall apply both under normal operating conditions and under conditions that are associated with failure of one or more engines and for which flight-performance characteristics have been established" ("Balance" section, Par. 2.3.2), etc.

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*Subsequent references to this source indicate only the Paragraph number. - Translator's Note: Due to unavailability of the ICAO document, quotations are retranslated here from the Russian.

The thrust of these and similar requirements is that the technical capabilities objectively inherent in the aircraft that enable it to avoid dangerous situations when one or another special situation arises (engine failure, icing, strong updrafts, etc.) are of practical value and do indeed ensure the necessary flight-safety level only under the mandatory condition that they can be brought to bear by a pilot with normal average qualifications and normal (not exceptional) natural mental and physical traits. Here it is also necessary to remember that these physical and especially mental traits of the individual may undergo certain changes under the influence of extraordinary circumstances of which he becomes aware.

In the preceding chapters, we pointed out those characteristics of an airplane (value of equilibrium angle of slip, relation between rolling and yawing motions, sign and magnitude of efforts at the controls, indication of optimum flight condition, etc.) that endow it with behavior after partial powerplant failure such that countering the divergent motion and subsequent flight with partial and unbalanced thrust do not require exceptional piloting technique, attention, or expenditure of physical energy from the pilot.

However, there are other technical characteristics of the airplane that are just as important for safe continuation of flight.

First of all, it is necessary that an engine failure not render inoperative such vitally important systems of the aircraft as /180 its control, fuel, electrical, hydraulic, and other systems. In consideration of this, the ICAO standards include the requirement that every aircraft be provided with "sufficiently workable measures to ensure continued functioning of the basic auxiliary systems in the event of engine failure" (Chap. 4, "Design and Construction," Par. 4.1.6). "The powerplant must be accommodated and mounted in such a way that each engine with its associated systems can be controlled and can function independently of the other groups and in such a way that a failure in the performance of any of the accessories and systems cannot result in a loss of power exceeding that incurred on total failure of the critical engine" (Chap. 7, "Powerplant," Par. 7.2.1).

The ICAO International Standards require conformity to specific conditions on partial powerplant failures at various stages in a flight.

Climbing characteristics are set forth for route flight, expressed in terms of vertical velocity or trajectory inclination angle with one or two critical engines inoperative (depending on the total number of engines on the particular airplane) and remaining engines running at nominal power (Par. 2.2.3.2).

In this case, the ability to gain altitude is regarded as a kind of criterion indicating that the airplane has a certain range of possible level-flight speeds and that it has the minimum maneuvering capability necessary to proceed from the point of engine failure to the point of landing.

For the landing approach with partially inoperative powerplant, the standards also require that an airplane be capable of gaining altitude with one engine out, but, in contrast to the previous case, at maximum landing weight (the maximum takeoff weight figured in the standards pertaining to route flight). The considerations dictating this requirement are similar to those set forth above, but with the added requirement that the airplane be capable of climbing out for a second approach on partial thrust: "In the event of an unsuccessful landing approach with the critical engine inoperative, and in the appropriate configuration, the airplane must be capable of continuing flight to a point from which it can make a second landing approach" (Par. 2.2.2.2).

For takeoff, the ICAO standards for airworthiness of aircraft provide for specification of a design failure point (which corresponds to the notion of critical takeoff speed that we used in Chap. V), from which the trajectory of a continued takeoff with the critical engine inoperative is computed. Here the remaining engines are run "within the limitations on their takeoff power, /181
but at the end of the period for which takeoff power may be used, the airplane must be capable of a continued climb with the critical engine out and the other engines running at no more than maximum continuous power to an altitude that the airplane can hold and at which it can circle the airport" (Par. 2.2.2.1). The corresponding paragraphs of the airworthiness standards state quantitatively the rates of climb required in this case for various aircraft classes. It is specifically stated that "the aircraft must retain controllability in the event of unexpected failure of the critical engine at any time during takeoff with the piloting techniques indicated in its flight manual for the takeoff and aborted-takeoff trajectory segment (Par. 2.3.1.2).

The need to provide the pilot with "quick-acting and dependable means of determining the time at which the critical point is reached" is also stated.

It is important to note that flight characteristics with partial and unbalanced thrust are considered in the ICAO airworthiness standards not only from the standpoint of their intrinsic importance as one of the possible important flight situations, but also as a criterion defining certain properties of the airplane in normal flight with its powerplant fully operative.

Thus, the safe takeoff speed for determination of the flight performance characteristics of an airplane after liftoff from the ground or the water corresponds, according to the definition in Par. 2.3.1.3, to the speed at which "an adequate margin with respect to liftoff speed and to the minimum safety speed at which the airplane remains controllable after critical-engine failure is ensured." This general definition is expanded in specific terms in the section on "Acceptable Methods of Establishing Conformity of Aircraft Flight Characteristics to Specification," where the following method is recommended for determining minimum safety speed: "The minimum safety speed is such that when any one engine is switched off at this speed the controllability of the airplane can be restored with one engine inoperative and the airplane can be held in straight-line flight at zero angle of yaw or at an angle of roll not exceeding 5°. Between engine shutdown and full recovery of controllability, the pilot shall not be called upon to exhibit exceptional skill or subjected to excessive mental or physical strain in preventing any loss of altitude beyond that which is inevitable with the deterioration of performance characteristics or any change in heading by more than 20°; during this time, the airplane shall not assume any dangerous spatial attitude... Holding the aircraft at this speed in steady straight-line flight after recovery of controllability and before rebalancing shall not require application of an effort greater than 200 /182 pounds ($\sim$81.5 kg)* to the rudder pedals, and the crew must not be forced to reduce the power output pf the remaining running engines" (Par. 4.2.1).

Certain national standards — including the USSR's airworthiness standards for civil aircraft — also make provision for use of unbalanced-thrust flight to check other handling characteristics of aircraft having no bearing on this flight situation. In the USA, for example, the directional and lateral controllability of transport aircraft is tested as follows ([22], Par. 4b.132). In flight with the critical engine not running (and, on aircraft with four or more engines, with two critical engines not running) and at a speed 1.4 times the liftoff speed, the pilot changes heading sharply by up to 15° in both directions with almost no roll, and then executes coordinated turns with up to 20° of roll under the same conditions, again in both directions. In all of these cases, the airplane must retain normal controllability and must not behave dangerously. It is assumed that an aircraft that has shown adequate controllability in such tests in unbalanced-thrust flight will meet the necessary requirements even better in normal flight with the powerplant fully operative.

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*According to USSR Standards, no more than 70 kg at the rudder pedals and no more than 20 kg at the control column in roll control.

The above flight-testing techniques are, of course, mentioned here only by way of example. Many other procedures of similar intent may be proposed (and do indeed exist). In all cases, however, flight with partial and unbalanced thrust remains of prime importance in the determination of aircraft airworthiness, both as one of the most important special flight cases whose outcome strongly affects safety and as an effective criterion that helps establish the stability and controllability of aircraft of a particular type in general.

2. ELEMENTS OF AIRCRAFT FLIGHT TESTS WITH PARTIAL AND UNBALANCED THRUST

Most of the data needed for evaluation of an airplane's behavior on sudden unilateral engine failures and in subsequent unbalanced-thrust flight can be determined by calculation. However, experience has shown that the agreement between the calculated results and reality may vary in rather broad limits, especially for experimental and test aircraft whose designs incorporate qualitatively new elements. /183

As a result, final verification of the characteristics of the airplane's motion in this flight situation (as, of course, in most others) requires performance of flight tests. Further, flight tests are the only method from which reliable practical recommendations can be developed as to piloting technique both at the instant of an unexpected engine failure and in the subsequent flight up to and including landing.

Experimental determination of flight characteristics with unbalanced thrust is now a mandatory element of the flight-testing programs for all aircraft having two or more engines.

All characteristics subject to determination in these tests can be broken down arbitrarily into two basic groups:

1) the characteristics of the airplane's divergent nonsteady motion immediately after a one-sided engine failure, and

2) characteristics of steady flight with partial and unbalanced thrust.

This subdivision is, of course, quite arbitrary. A number of important cases in which it would be difficult to hold strictly to it could be cited. Thus, for example, an engine failure on takeoff first requires countering of the divergent yawing and rolling motions and eventually a steady climb. Nevertheless, this subdivision is quite workable for determination of the composition and sequence of unbalanced-thrust test flights.

Like the technique used in performing them, the specific list of points covered by the program of flight tests naturally varies substantially for aircraft differing in type, weight, and powerplant makeup.

However, certain general, typical principles in the design of these programs and techniques are applicable to an overwhelming majority of test aircraft.

It must be noted first of all that, as is evident from the preceding chapters, unbalanced-thrust flight characteristics vary widely: they vary for a given aircraft with changes in altitude, flight weight, configuration, the combinations of running and inoperative engines, etc. In flight tests, therefore, the corresponding characteristics of each aircraft are determined for various combinations of powerplant output, aircraft configuration, piloting technique, altitude, and speed in order to approach progressively the combination of these parameters that is least favorable (critical) for the particular case.

The traditional flight-testing principle of moving gradually from the simple to the complex and from the known to the unknown must be especially strictly observed in in-flight studies of the dynamics of an airplane with one-sided engine failures. Departures from the flight-plan sequence and transitions to more critical regimes before less critical regimes have been thoroughly studied (including decoding and analysis of the monitoring-instrument records) are categorically forbidden. /184

In accordance with the above, unbalanced-thrust tests must be performed:

1) at low altitudes (and especially near the ground) after medium- and high-altitude tests;

2) at low speeds after tests at cruising and high speeds;

3) with the critical engine switched off after engines with weaker influence on the airplane's motion have been switched off;

4) with abrupt thrust changes (for example, fuel-supply shutoff) after smooth throttling-down;

5) in the airplane's landing configuration after tests in the cruising and then in the takeoff configuration;

6) in unsteady divergent-motion regimes after testing in steady flight regimes, etc.

Apart from safety considerations, which dictate a certain sequence in the conduct of unbalanced-thrust tests, there is a definite relation between these tests on the one hand and certain points in the complete flight-testing program for the particular aircraft on the other. Thus, the airspeed indicator must be calibrated (its aerodynamic corrections determined) before determination of any of the speeds characteristic for flight with partial and unbalanced thrust. In exactly the same way, the safe takeoff speed V_{safe} assigned for performance of continued takeoffs requires preliminary determination of the safety speed V_{sa}, etc.

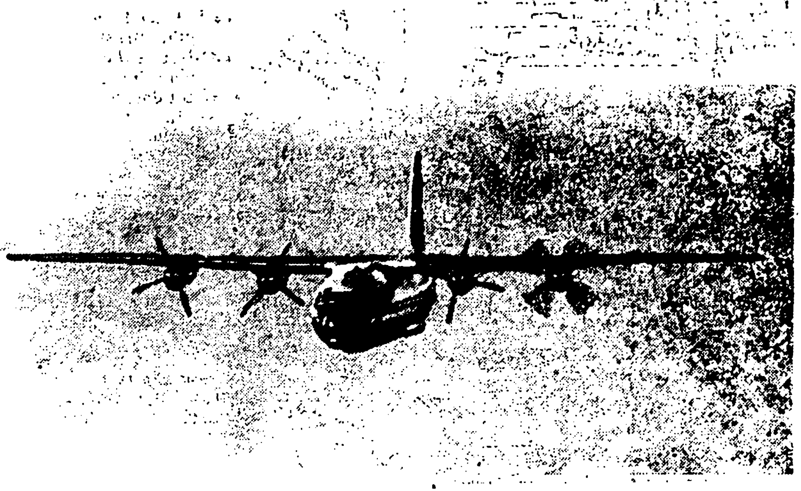

Figure 84. An-10 Aircraft in Flight with Three Engines Switched Off.

All maneuvers necessary for evaluation of conformity to the airworthiness standards must in all cases be performed during flight testing of each airplane.

In flight tests, the airplane is, as a rule, flown under conditions that will practically never be encountered in normal operation. This is done to determine the controllability and power margins that remain unused in simpler cases (which are, accordingly, more probable in normal operation). Figure 84 shows one of these conditions: straight-line flight with slow loss of altitude by a four-engined An-10 airplane with three engines switched off and only one (outboard, no less) running.

The monitoring and recording instrumentation needed for tests /185 of an airplane in unbalanced-thrust flight does not generally require anything in addition to the outfit needed for determination of its other characteristics, namely: speed recorder, barograph, gyrograph, accelerograph, inclinograph, automatic recorders for the deflections of the aircraft and engine controls, automatic recorders for the efforts required at the controls, and automatic recorders for engine-performance parameters. It is also highly desirable to have an automatic recorder or visual indicator for the angle of slip.

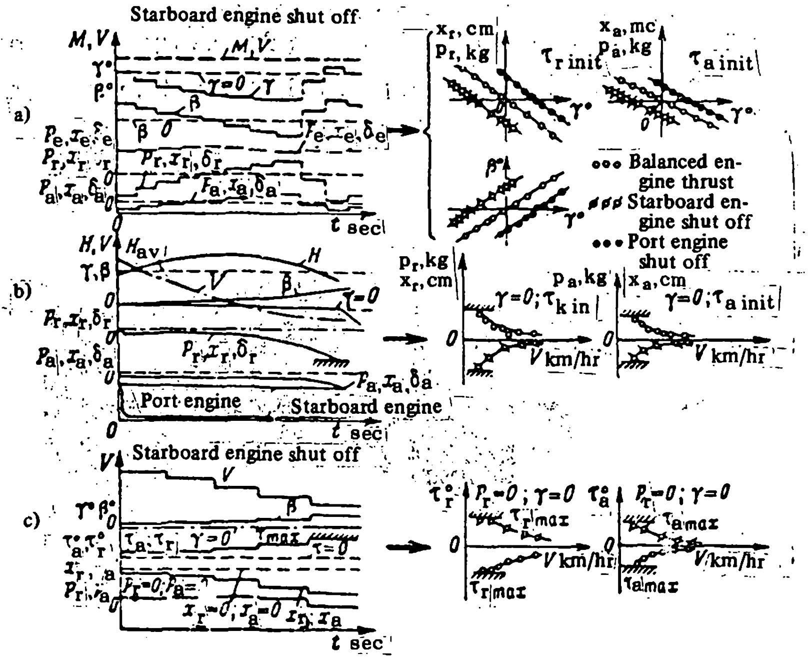

Figure 85. Diagram of Processing of Flight Records to Determine Basic Steady-Flight Characteristics of a Two-Engined Airplane with Unbalanced Thrust.

The characteristics of steady flight with one and two (on three- and four-engined aircraft) engines switched off are determined in straight-line flight conditions at various angles of roll (basically in the range between $\gamma = 0$ and $\gamma \sim \beta = 0$), several speeds, ranging from top speed at the given thrust to $\sim 1.2V_{min}$, with the running engines set to full and cruising thrust, in all basic regular configurations of the airplane, etc. By processing the data obtained in these flights, such as those shown in Fig. 85,* it is possible to determine the values of V_{min} and $V_{max} = f(H)$; $V_y = f(H)$, $\delta_r = f(\gamma, V)$, $\delta_a = f(\gamma, V)$, $P_r = f(\gamma, V, \tau_r)$, $P_a = f(\gamma, V, \tau_a)$, and the other basic quantities characterizing the behavior of the airplane in steady flight in various configurations and with various degrees of thrust imbalance, on the basis of which the range of capabilities of the aircraft in these cases can be established and optimum flight regimes and piloting procedures can be arrived at for the most rational utilization of these capabilities. /186

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*Figure 85 is borrowed from the book by M.G. Kotik, A.V. Pavlov, I.M. Pashkovskiy, N.G. Shchitayev [7], which sets forth in detail procedures for flight-testing of aircraft, including those involving partial and unbalanced thrust.

The characteristics of the nonsteady motion at the instant of one-sided engine failure are determined with observance of the above procedure in such a way that this series of test regimes culminates in simulation of abrupt shutdown of the critical engine with the powerplant operating at full thrust and the airplane moving at a speed $V = 1.2\text{-}1.4\ V_{min}$, with countering of the resulting divergent motion after a specified number of seconds (usually 5) or on reaching the maximum permissible angle of roll. This time ($\Delta t_{\gamma lim}$ or $\Delta t_{\beta\ lim}$) is usually taken as the basic quantitative characteristic of the airplane's motion in this case. The values of δ_r, δ_a, P_r, and P_a required of the pilot to counter the roll and yaw must be determined simultaneously.

The nonsteady unbalanced-thrust flight conditions whose parameters must be determined in flight tests also include turns toward both the running and the nonrunning engines, with angles of roll not exceeding the established γ_{max} and ensuring observance of the condition $V_y > 0$. /187

Aborted and continued takeoffs occupy a special position in tests of an aircraft in flight with unbalanced thrust. It goes without saying that these assignments, and the continued takeoffs in particular, must be carried out only after complete investigation of the airplane under all other items of the program for these tests, in particular after definite establishment of the values of $V_y = f(V)$, $\delta_r = f(V)$, $P_{r_{\tau=0}} = f(V)$ with the critical engine out in the airplane's takeoff configuration.

The points at which critical-engine failure is simulated in the series of aborted and continued takeoffs must be shifted progressively in opposite directions, i.e., from low to high takeoff-run speeds on aborted takeoffs and from steady climb to the lift-off point and then to even lower speeds, at which the airplane is still running along the ground, in the case of continued takeoffs. In the latter case, the limit to which the engine-shutoff speed can be lowered can be established by effects of two types: an excessive increase in the continued-takeoff distance or excessive values of the δ_r and P_r needed to keep the airplane from yawing. In the interests of more reliable determination of V_{cr} as a function of G, L_{rwy} and other parameters influencing it, it is desirable that the point of intersection of the $L = f(V_{fail})$ curves for aborted and continued takeoffs be obtained in the course of the tests.

All elements of aircraft tests in unbalanced-thrust flight must be accompanied by amplified quality ratings from the pilots. This is necessary both for formulation of practical recommendations for piloting in all of the diverse cases of flight with inoperative lateral engines and to confirm that control of the airplane does not require "exceptional skill and excessively strained attention" in any of these cases.

REFERENCES /188

1. Bolotnikov, V.F., Safety of Climbing Regimes, Vestnik Vozdushnogo Flota, 1939, No. 8.
2. Vedrov, V.S. and Tayts, M.A. Letnyye Ispytaniya Samoletov (Flight Tests of Aircraft), Oborongiz, 1951.
3. Gallay, M.L. Comparative Quantitative Evaluation of Flight Safety of Aircraft of Various Configurations in the Case of Partial Failure of Their Powerplants, Trudy Vysshego aviatsionnogo uchilishcha GVF, No. 8, Leningrad, 1960.
4. Gallay, M.L., Polet Samoleta s Nepolnoy i Nesimmetrichnoy Tyagoy (Flight of Aircraft with Partial and Unbalanced Thrust), Izd-vo Aeroflota, 1961.
5. Gerathewohl, Psikhologiya Cheloveka v Polete (Human Psychology in Flight), IL, 1956.
6. Klyachkin, A.L., Application of Probability Theory to Analysis of Engine Failures on Multiengined Aircraft, Trudy Rizhskogo Instituta GVF, No. 40, 1964.
7. Kotik, M.G., Pavlov, A.V., Pashkovskiy, I.M., and Shchitayev, N.G.,Letnyye Ispytaniya Samoletov (Flight Tests of Aircraft), Mashinostroyeniye, 1968.
8. Lebedev, A.A., Strazheva, I.V., and Sakharov, G.I. Aeromekhanika Samoleta (Aircraft Aeromechanics), Oborongiz, 1955.
9. Lebedev, N.V., Osobennosti Pilotirovaniya Samoleta "Petlyakov-2" (Handling Pecularities of the "Petlyakov-2" Airplane), Central Aerohydrodynamics Institute, 1943.
10. Ostoslavskiy, I.V., Aerodinamika Samoleta (Aircraft Aerodynamics), Oborongiz, 1957.
11. Okhonskiy, A.I., Investigation of the Il-14 Airplane in Flight on One Engine, Grazhdanskaya Aviatsiya, 1958, No. 1.
12. Pyshnov, V.S., Povedeniye Samoleta pri Vnezapnoy Ostanovke Bokovogo Motora (Behavior of Aircraft on Sudden Shutdown of a Lateral Engine), NII VVS KA, 1942.
13. Rozenblat, M.V., Propeller Windmilling of Gas-Turbine Engines, Grazhdanskaya aviatsiya, 1958, No. 12.
14. Rozenblat, M.V., Piloting the Tu-104 Airplane with One Engine Running, Grazhdanskaya Aviatsiya, 1957, No. 9.
15. Sedov, G.A., Speed and Altitude, Vestnik Vozdushnogo Flota, 1959, No. 8.
16. Siforov, V.I., Reliability Calculation Methods for Systems Containing Many Elements, Izvestiya AN SSSR, OTN, No. 6, 1954.
17. Ushakov, S.F., Ten Hours Behind the Frontline, Aviatsiya i Kosmonavtika, 1966, No. 6.
18. Khmel'nitskiy, P. and Levin, D., When Three Engines are Running, Grazhdanskaya Aviatsiya, 1967, No. 1. /189
19. Chestnov, A.V., Letnaya Ekspluatatsiya Samoleta (Flight Operation of Aircraft), Voyenizdat, 1962.
20. Interavia, No. 3897, Air Letter, 1958.

21. Yumashev, A.B., In High-Altitude Flight, in: Komandarm Krylatykh (Army Air Commander), Izd-vo "Liyesma," Riga, 1967.
22. Airplane Airworthiness (Transport Categories), Federal Aviation Agency, USA, 1962.
23. International Standards, Airworthiness of Aircraft. Annex 8 to the Convention on International Civil Aviation. Fifth Edition - April 1962, International Civil Aviation Organization.

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